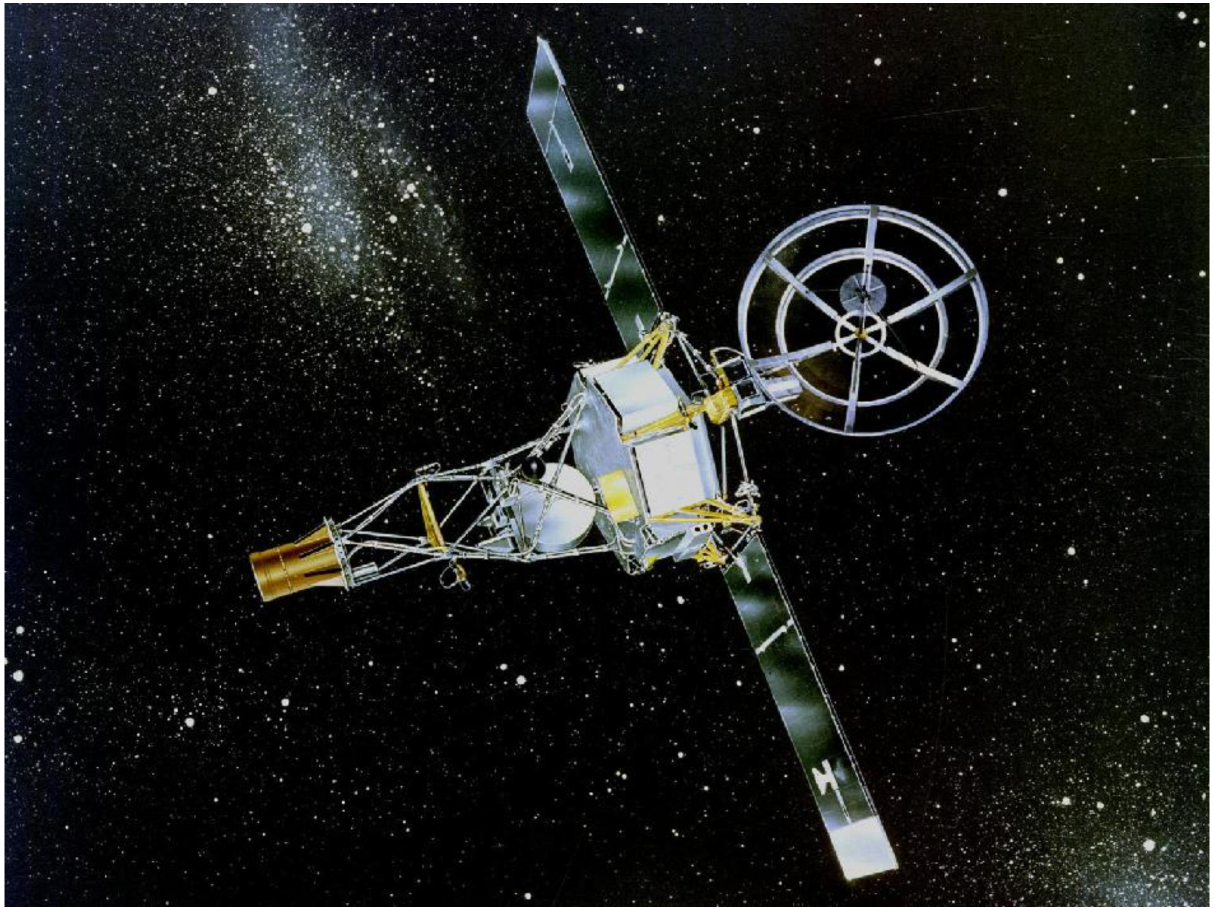
Microwave observations of planetary atmospheres

François Forget
(LMD, CNRS, Paris)
E. Lellouch (LESIA)
The MAMBO team

First interplanetary space probe = first microwave radiometer

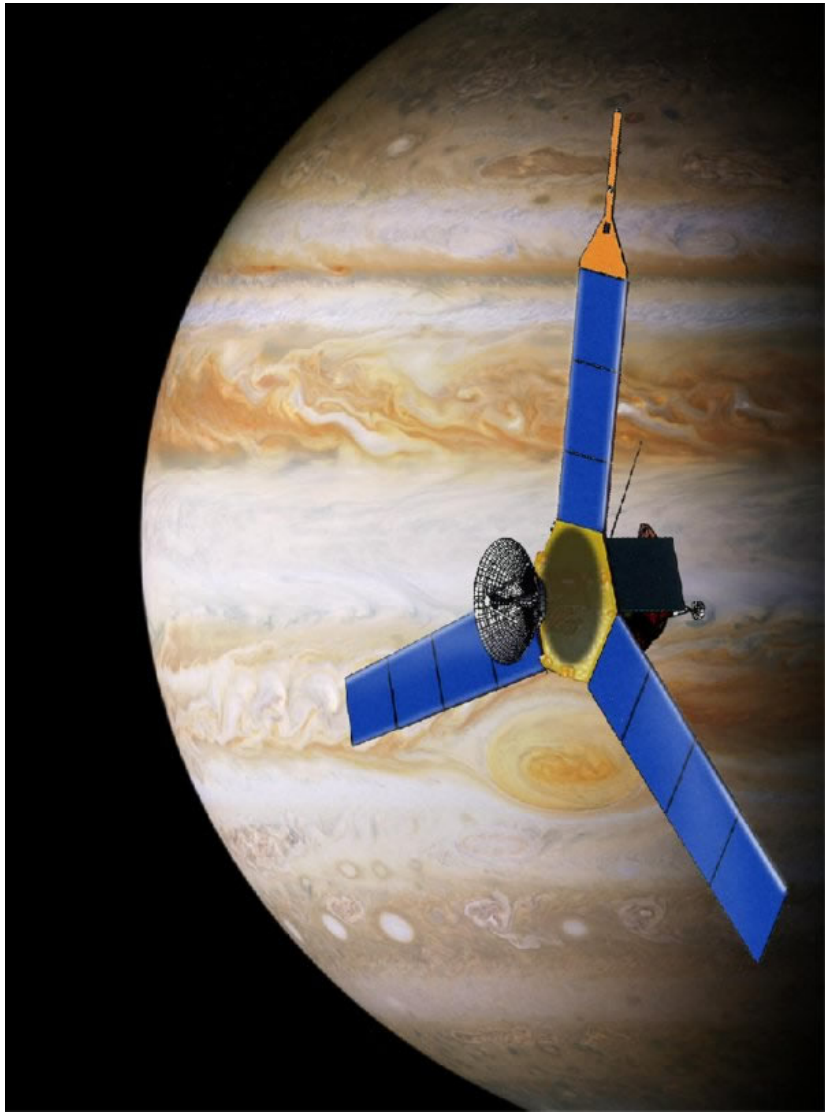


December 1962: Mariner 2 microwave radiometer (λ=1.9 cm) demonstrates that the hot microwave emission of Venus comes from the surface (limb darkening)

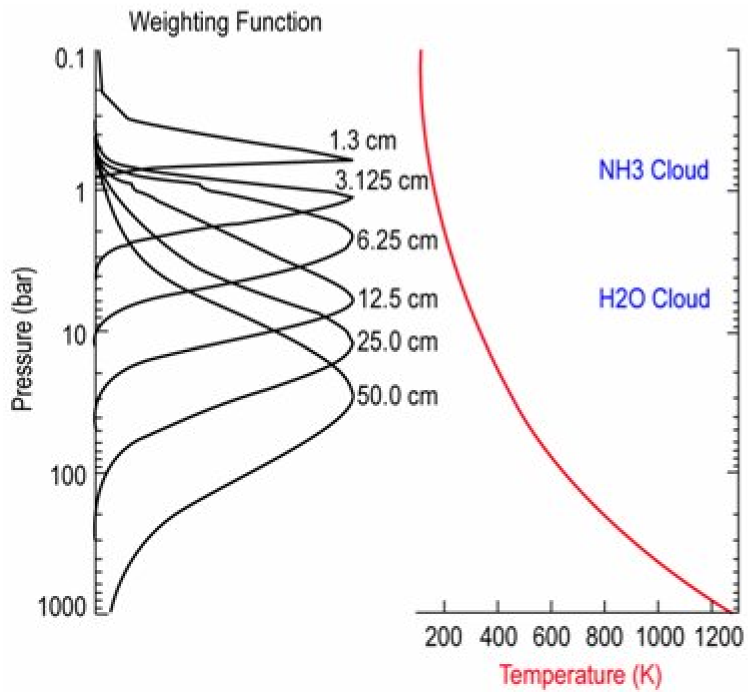
Planetary Science and microwave sounding

- Mariner 2…
- MIRO on Rosetta :
  - 190 GHz (1.6 mm) and 562 GHz (0.5 mm)
  - 30 cm antenna + CTS
  - CO, CH3OH, NH3 and three, oxygen-related isotopologues of water, H2 16O, H2 17O and H2 18O
- Juno on Jupiter
- More « Earth –like instrument » proposed for Mars, Titan, etc…

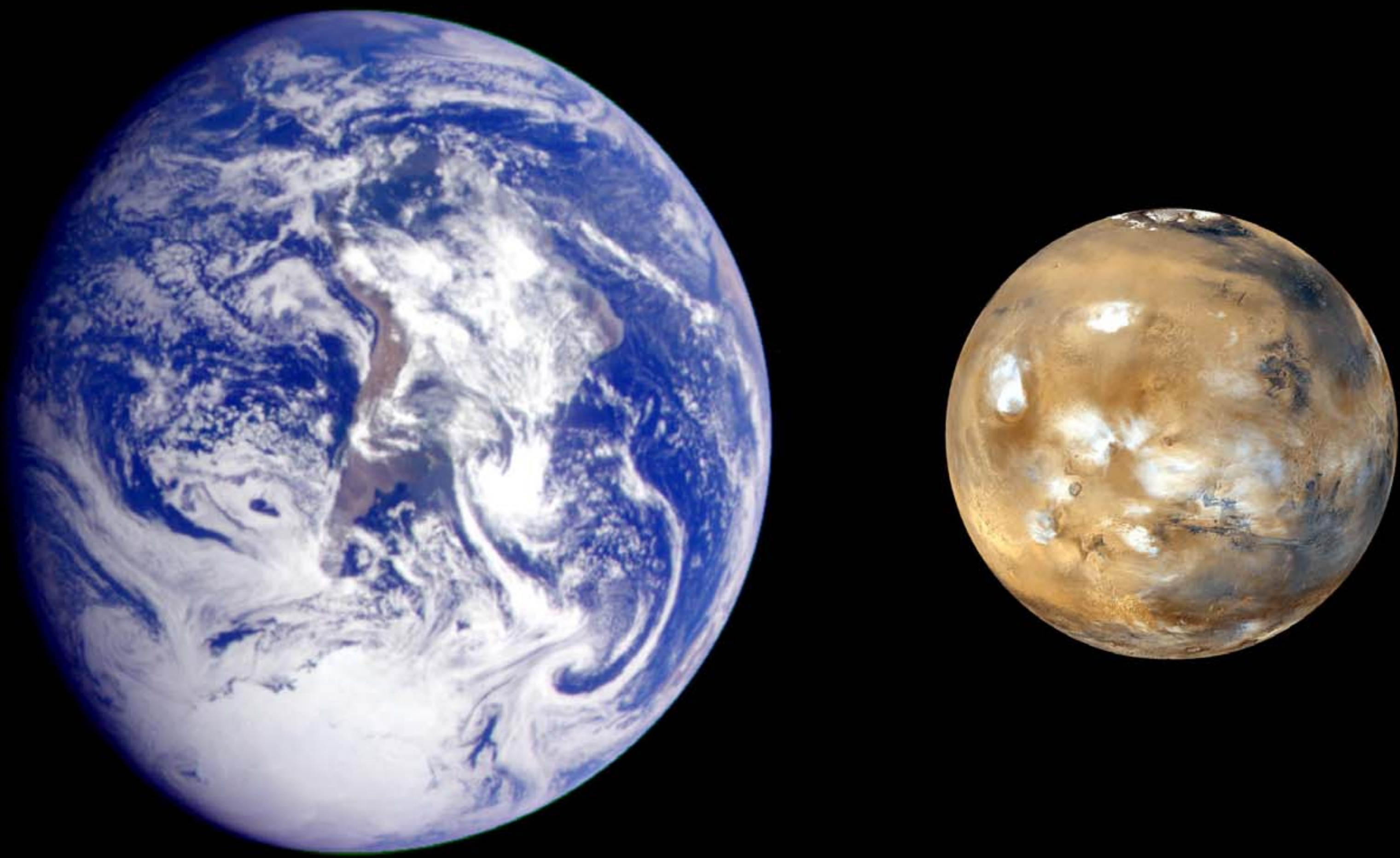
Juno Microwave Radiometer (Launch: august 2011):
to probe deep in the atmosphere of Jupiter



MWR probes NH3, H2O

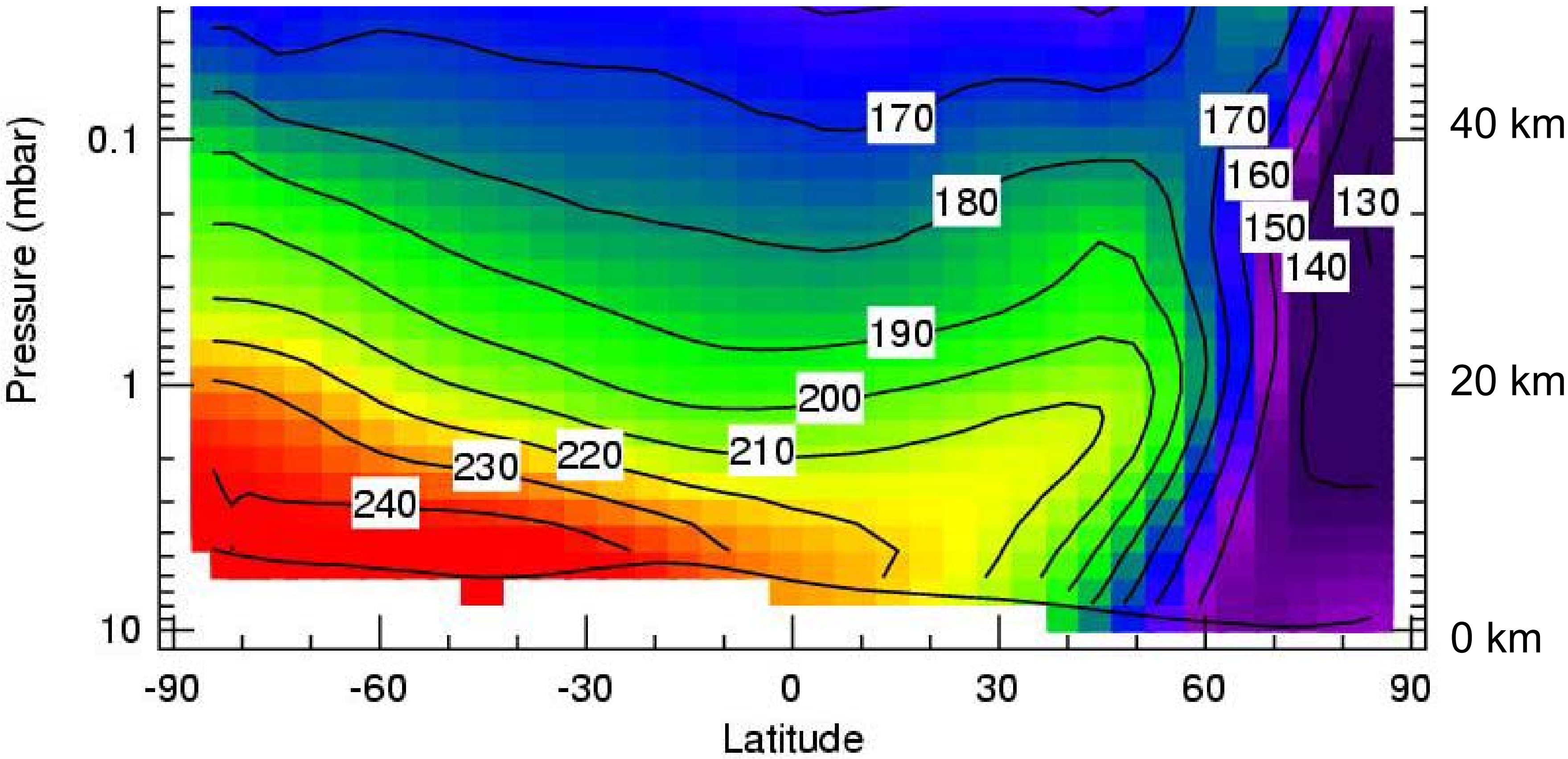


An example to study Mars atmosphere

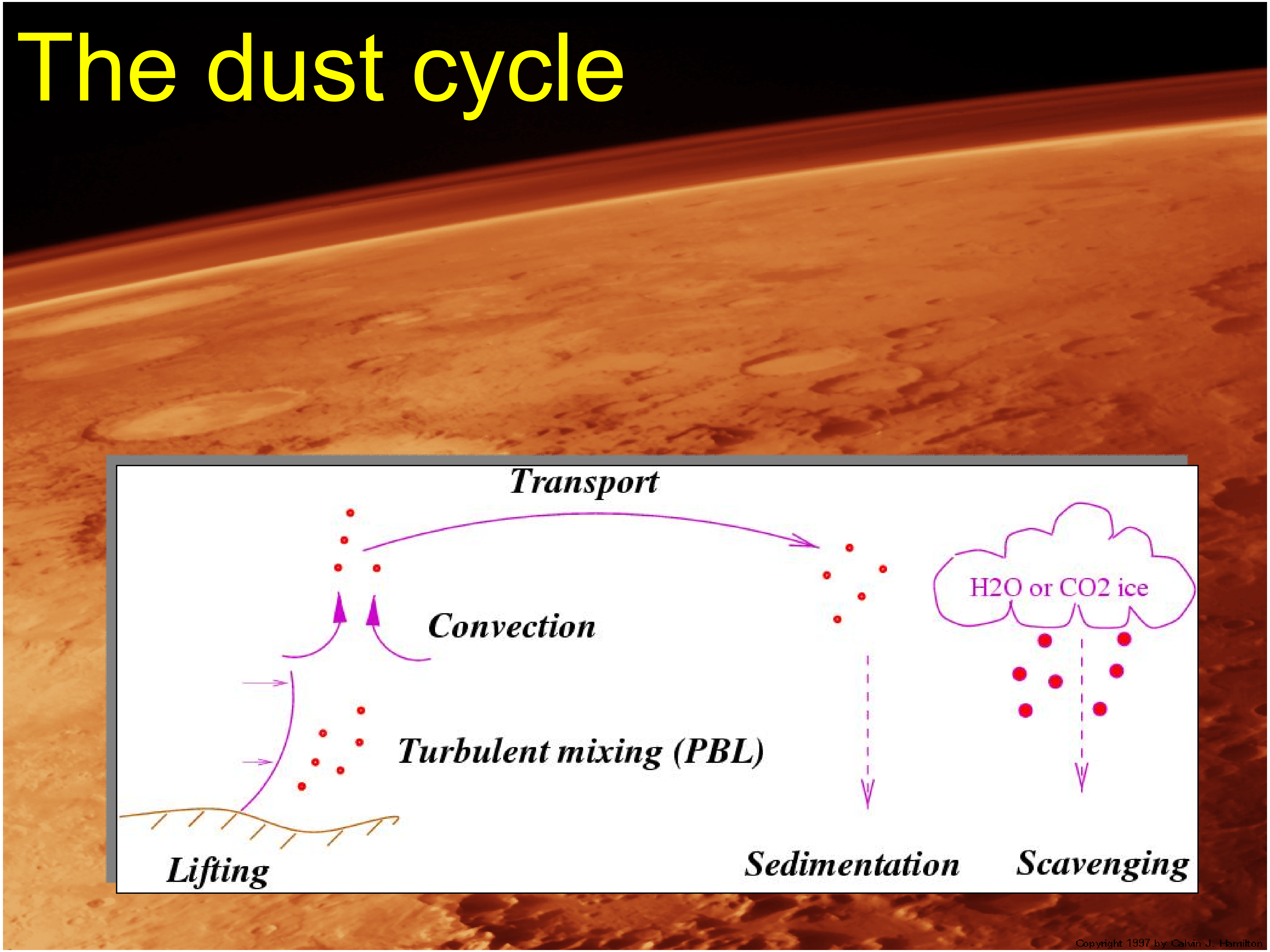


Atmospheric temperatures

(Northern winter; Mars Global Surveyor Observations
(Spectrometer TES , CO2 15 µm band inversion)

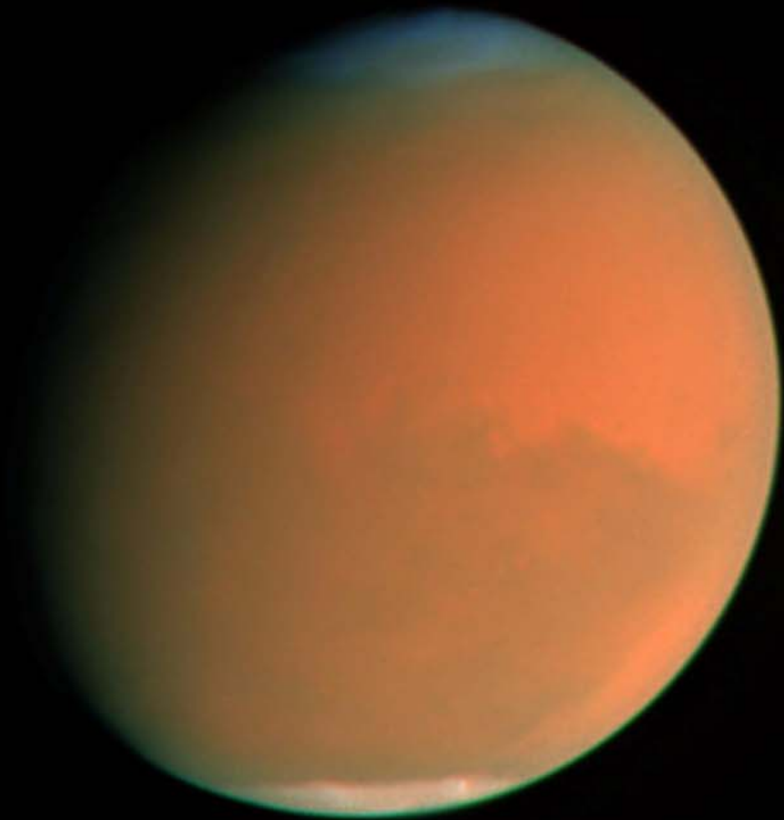


The dust cycle



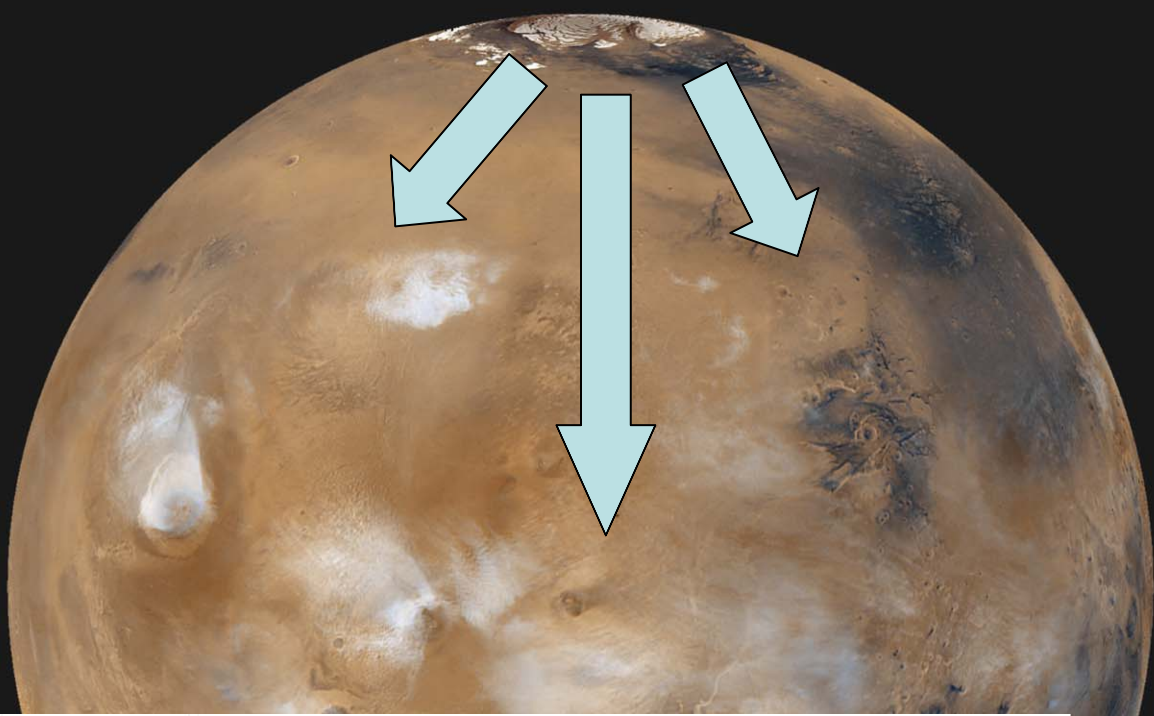
Global dust storms

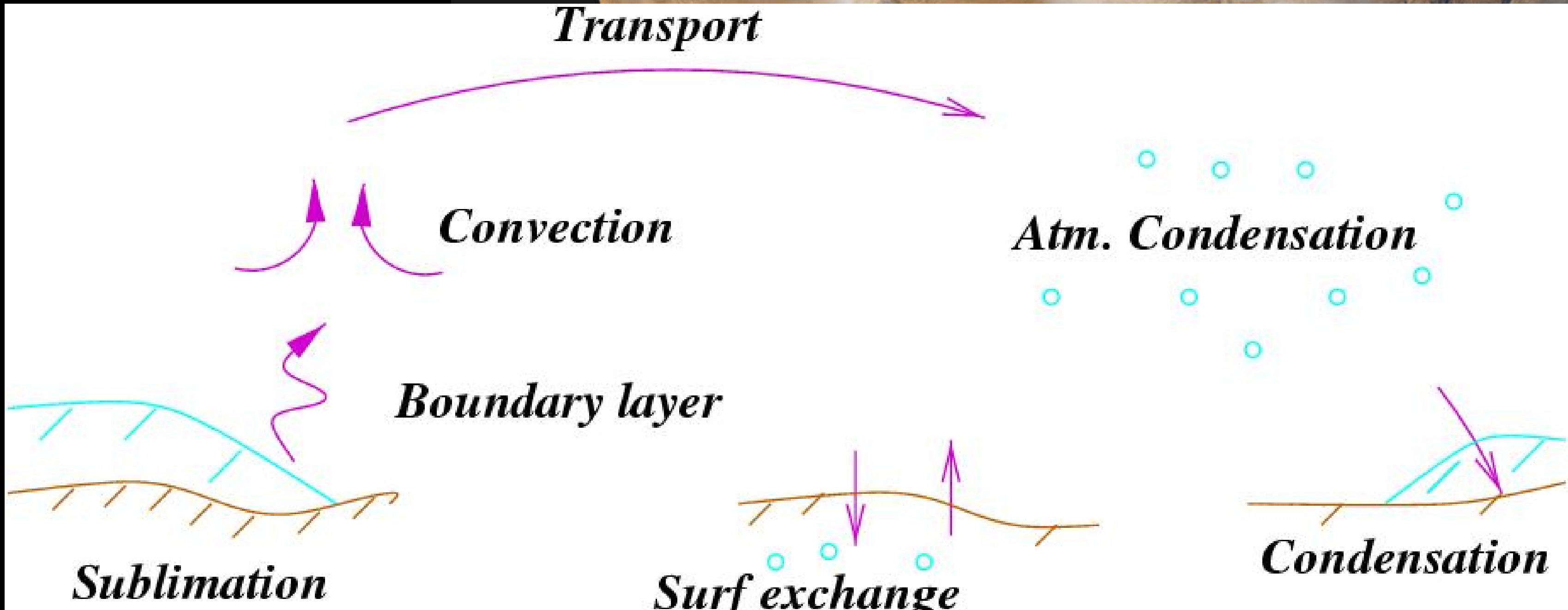
June 26, 2001



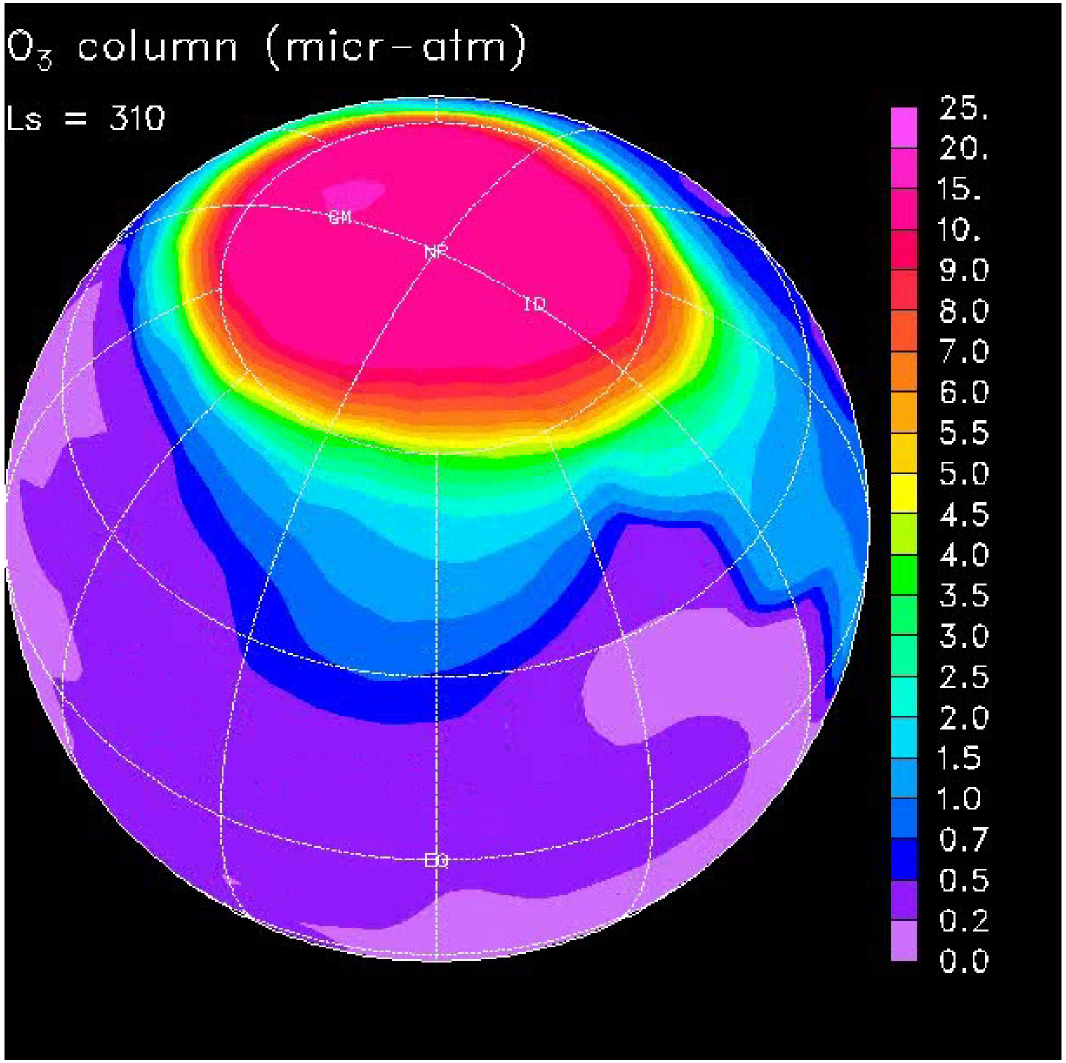
September 4, 2001

The water cycle





An active chemistry



SIMULATION : Ozone column at the end of northern winter (movie : 4 pictures / day)
(Lefevre, Lebonnois and Forget 2004)

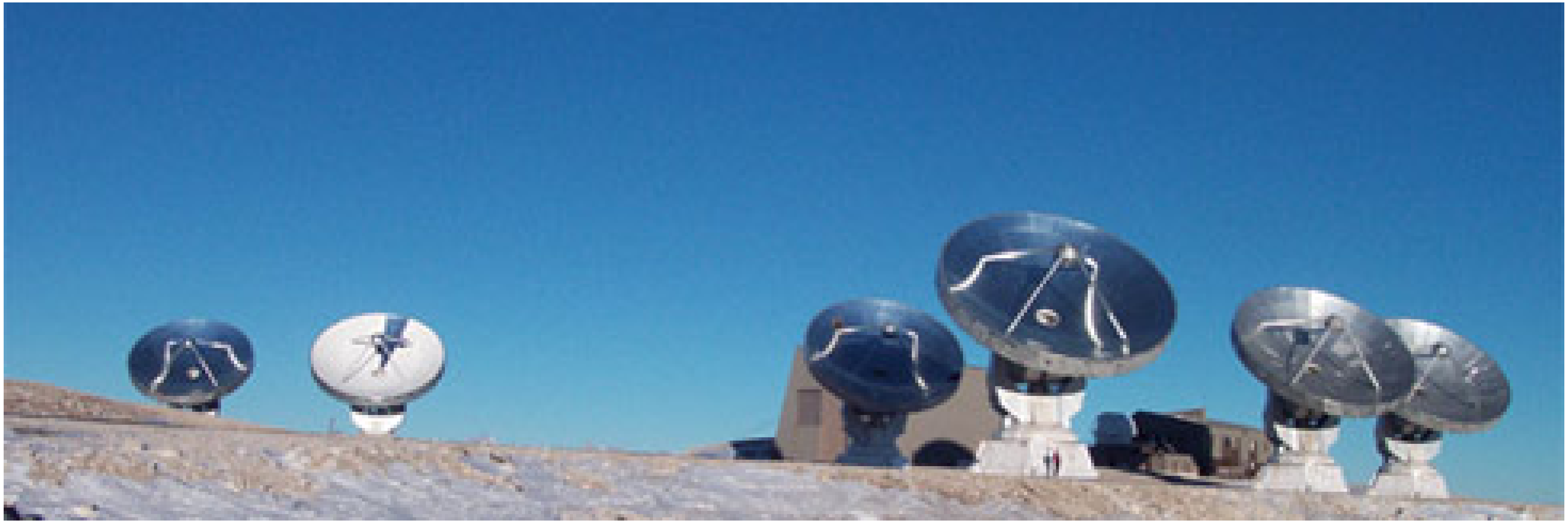
Available observations of Mars atmosphere from Orbit

- Profile : Mostly temperature below 50 km
  - IR sounding
    - TES on Mars Global Surveyor, 1997-2005),
    - PFS on Mars Express (2004-present)
    - MCS on Mars Reconnaissance Orbiter (2006-present)
  - A few radio occultation and stellar occultation profiles
- Column: Water vapor, ice, dust aerosols
- Ozone observed with UV spectrometer SPICAM / Mars Express (2004)

Other key measurements obtained from Earth, in the microwave (thermal emission)

(Encrenaz, Lellouch, Moreno, Clancy, etc.)

- Doppler shift winds
- Temperature monitoring
- $H2O$, HDO, CO , ^{13}CO column
- Detection of H2O2



Microwave observations of the Martian atmosphere from orbit ?

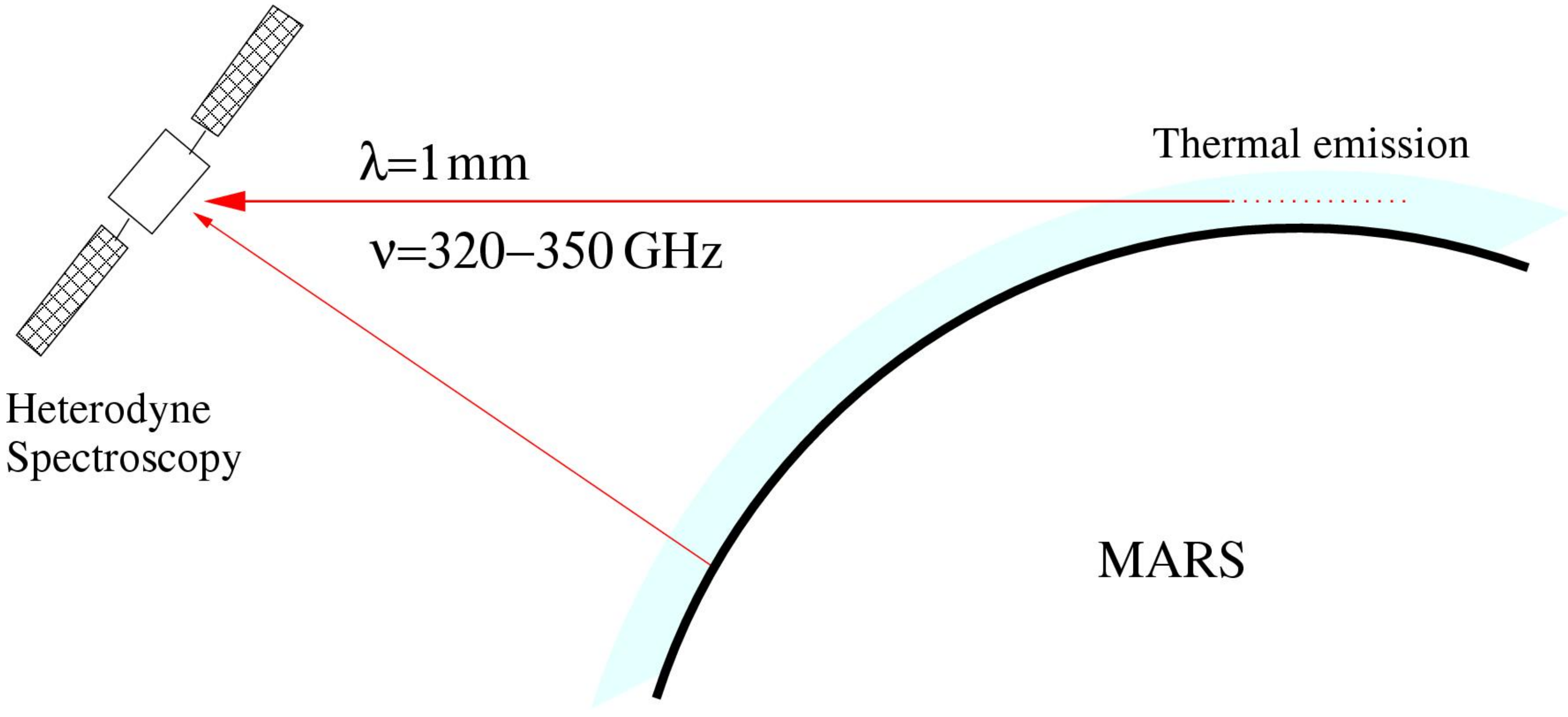
- **Lots of gas rotational lines available**
  - especially CO, used to retrive temperature and winds : 115, 230, 345, 460, 575 GHz, etc.)
  - H2O
  - Many other species : O3, H2O2, HDO, HO2, NO, etc…
- **Which frequency ?**

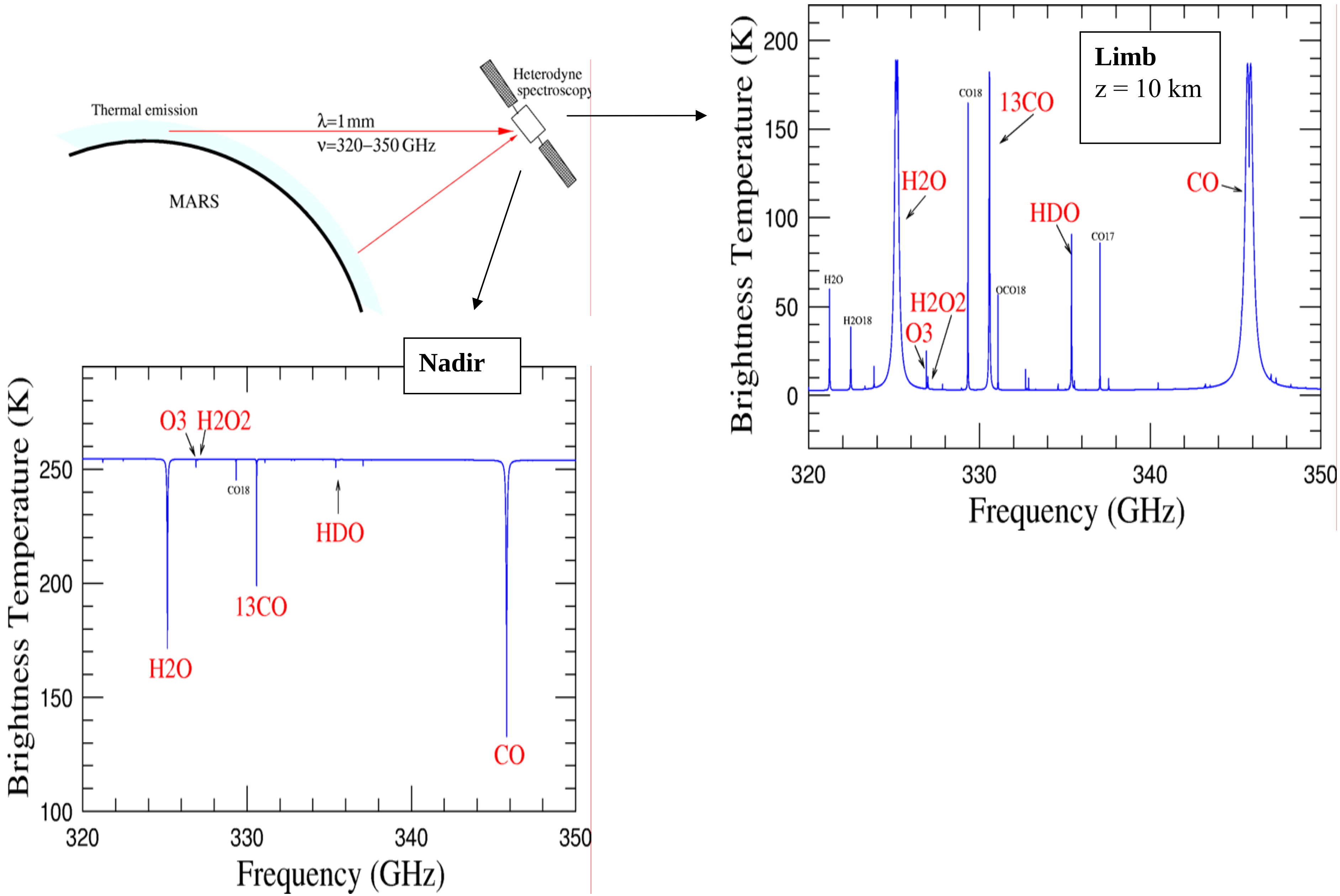
⇨ **Compromise :**

  - Higher frequency : higher noise
  - Lower frequency : larger antenna required for a given beam size
  - Detailed choices driven by available gas lines (especially CO)
- **Spectrometer can be used looking Nadir, but ground breaking science is performed by scanning the limb**

MAMBO

Mars Atmosphere
Microwave Brightness Observer

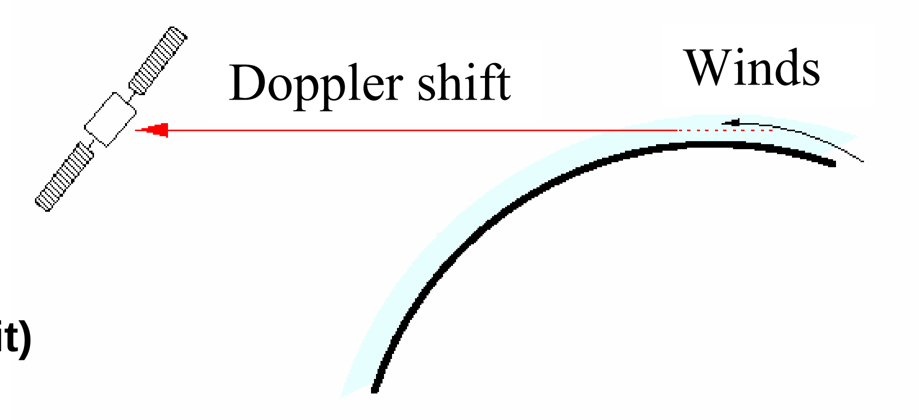




Thermal emission
λ=1 mm
ν=320–350 GHz
Heterodyne spectroscopy
MARS
Nadir
O3 H2O2
CO18
HDO
13CO
H2O
CO
Brightness Temperature (K)
Frequency (GHz)
Limb
z = 10 km
CO18
13CO
H2O
CO
HDO
CO17
H2O
OCO18
H2O18
H2O2
O3

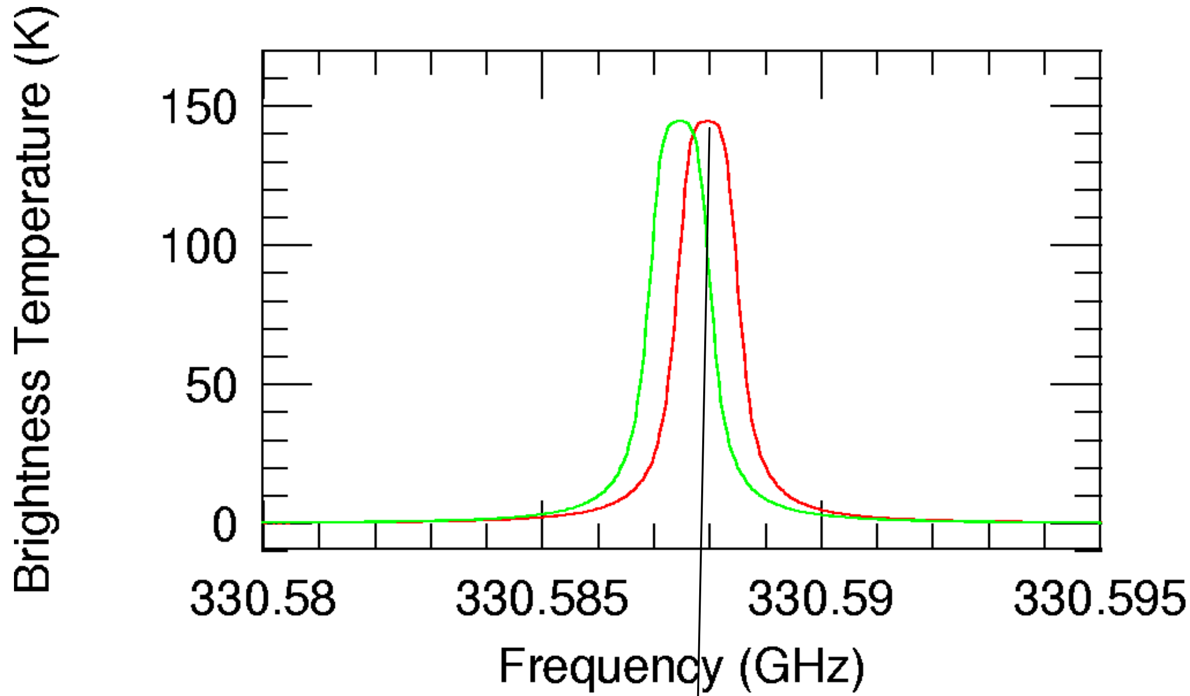
Science objective 1)
3D mapping of the wind
from 20 to 110 km

(cross-track wind: zonal wind in polar orbit)

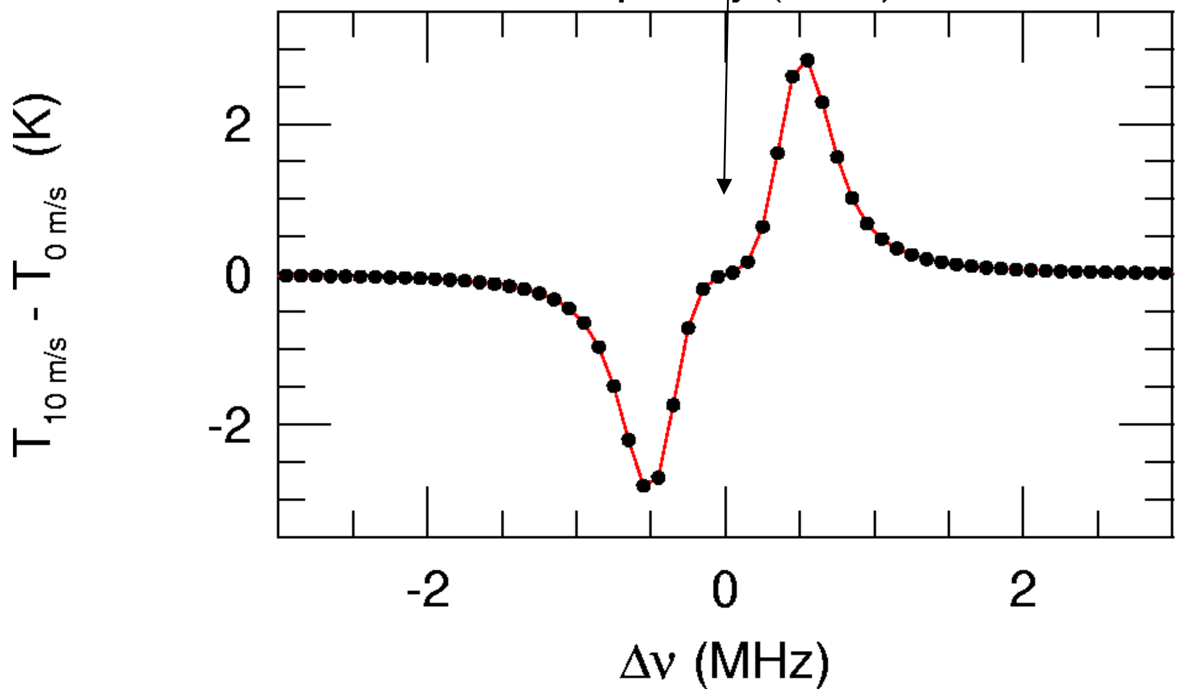


- Measurement of the Doppler shift on ^{13}CO et CO (10 m/s = 10 kHz)
-

Doppler shift of a 13CO at 50 km (exagerated)

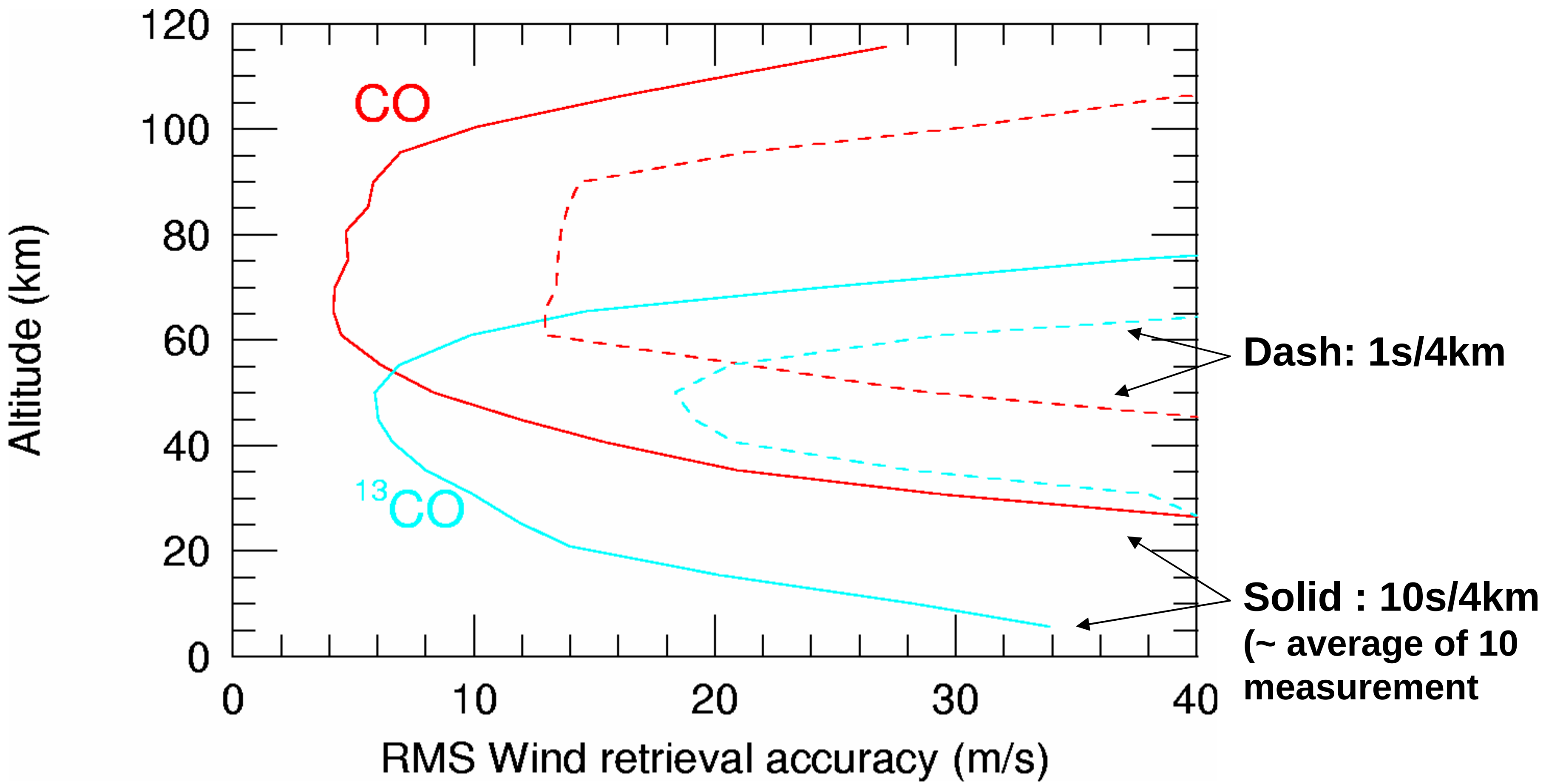


Actual difference between 10 m/s shifted spectra at MAMBO resolution,



Wind retrieval accuracy

(Monte Carlo simulation)



Science objective 1)
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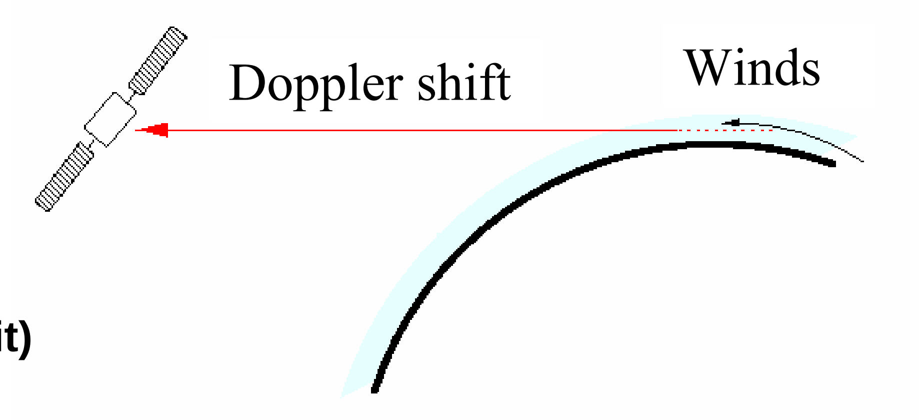


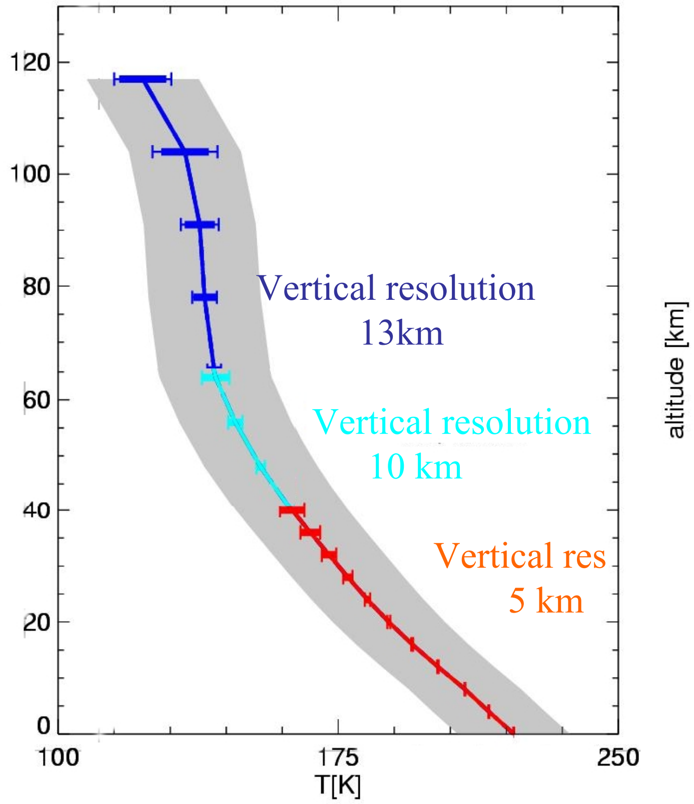
- Measurement of the Doppler shift on ^{13}CO et CO (10 m/s = 10 kHz)
- First direct wind observations from orbit
- Accuracy : ~10 m/s

=> This observations is crucial to study Mars Meteorology and climate because indirect estimation of the wind is difficult on Mars

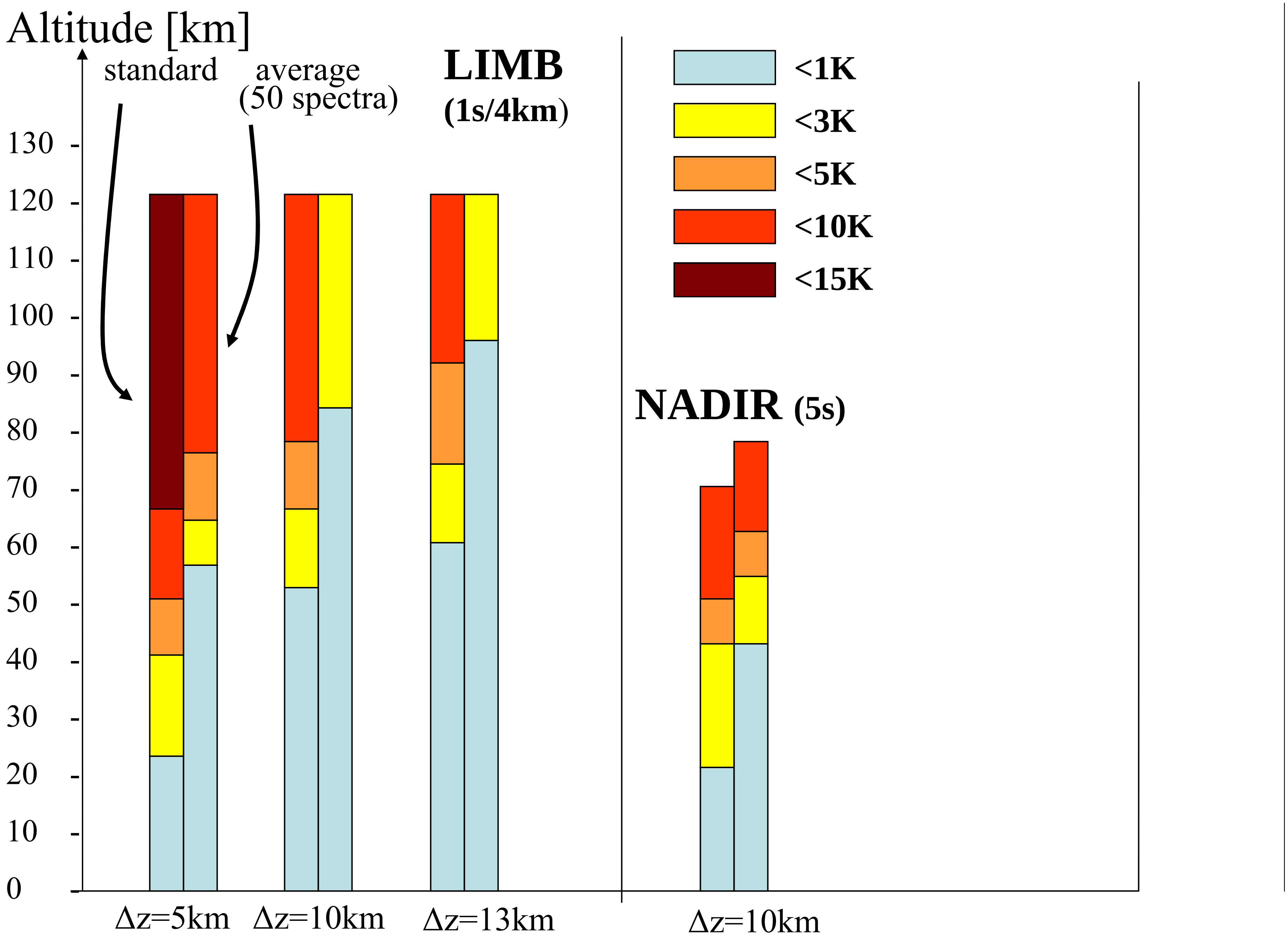
2) 3D mapping of **temperature** (0-120km)

- Inversion of CO and ^{13}CO
- Unprecedented sensitivity:
  - Insensitivity to aerosols (*affect IR below 40 km)*
  - Thermal emission a T
  - Well known line shape
  - Local thermal equilibrium (LTE) valid everywhere

(*major problem in the IR above 70 km)*



Simulated inversion using CO at 345.8 GHz
(Bordeaux Observatory - LMD)
Urban et al. 2004



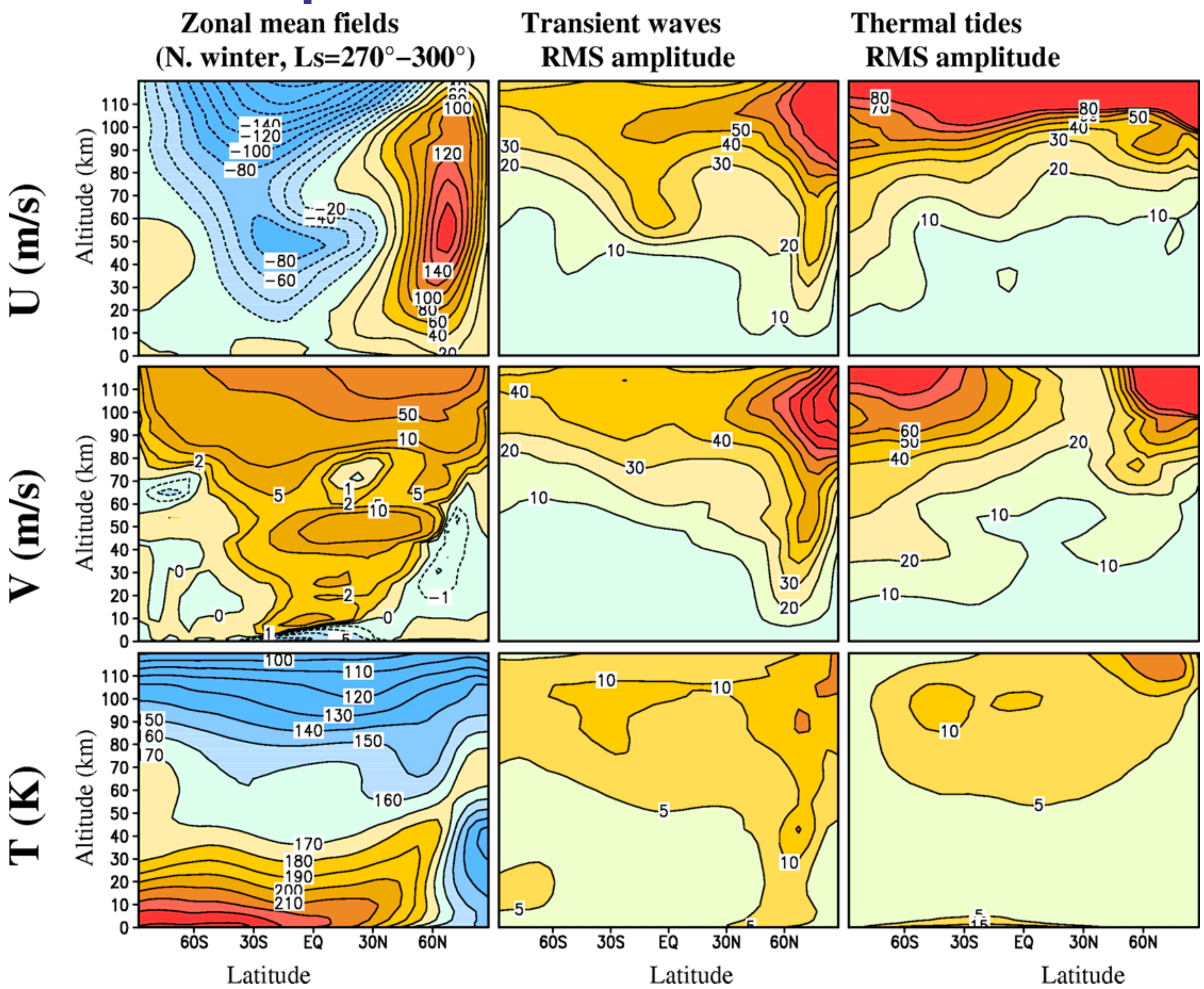
Altitude [km]
standard
average
(50 spectra)
LIMB
(1s/4km)
<1K
<3K
<5K
<10K
<15K
NADIR (5s)
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Δz=5km
Δz=10km
Δz=13km
Δz=10km

Example: Northern winter dynamics

The best part is above 80 km !

LMD GCM

Simulation:



Combining wind + temperature :

Winds

Température

Data assimilation

Meteorological model

4D circulation of the atmosphere between 0 and 120 km !

=> **Comparative meteorology**

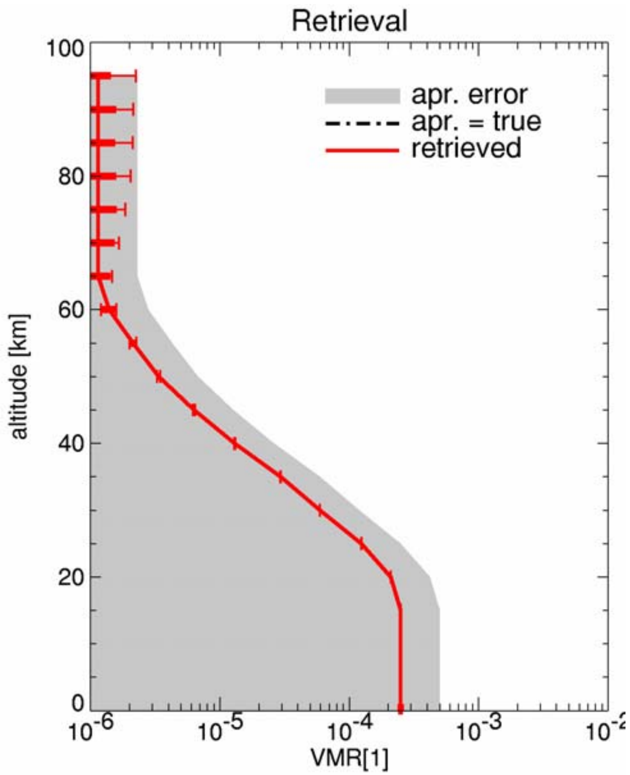
=> Synergy with Netlander

3) 3D mapping of
<u>water vapor</u> (0-60km)

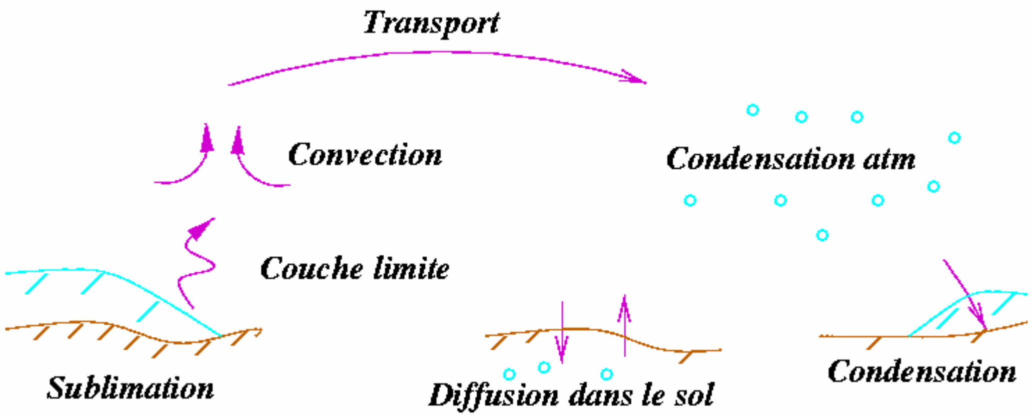
- Inversion of H_2O et HDO
  - Insensitivity to aerosols
  - High accuracy and sensitivity

- Water vapor + general circulation :

=> ***Water cycle, sources, sinks***

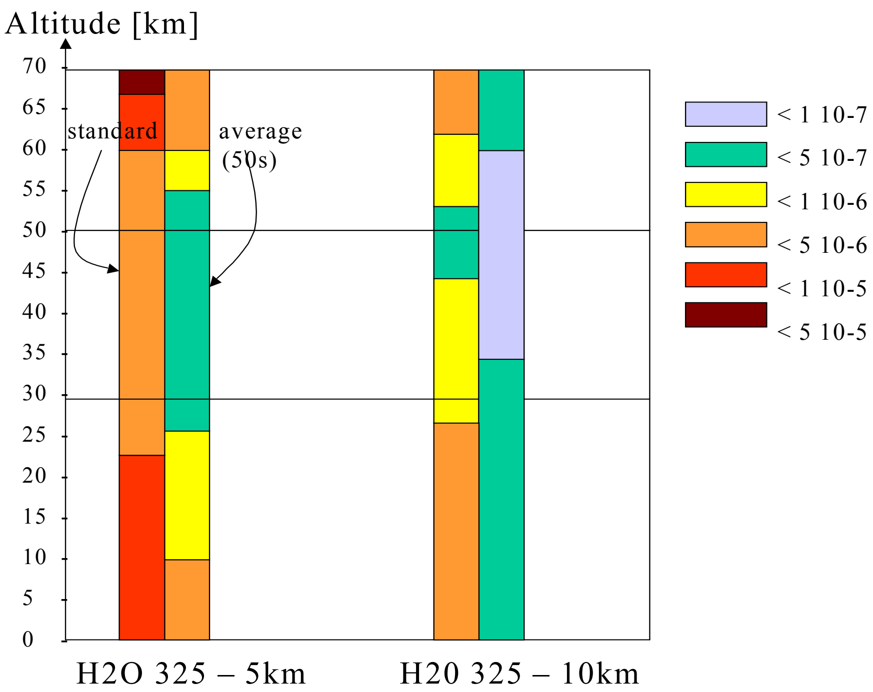


Simulated inversion of H2O at 325.15 GHz (Obs de Bordeaux-LMD))

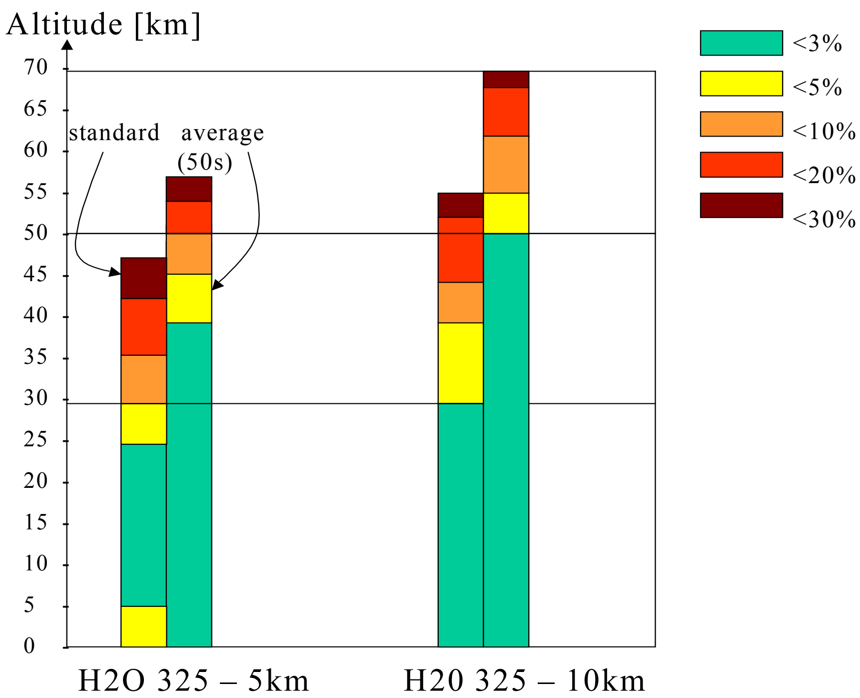


Water vapor profiles

Volume mixing ratio
RMS retrieval accuracy

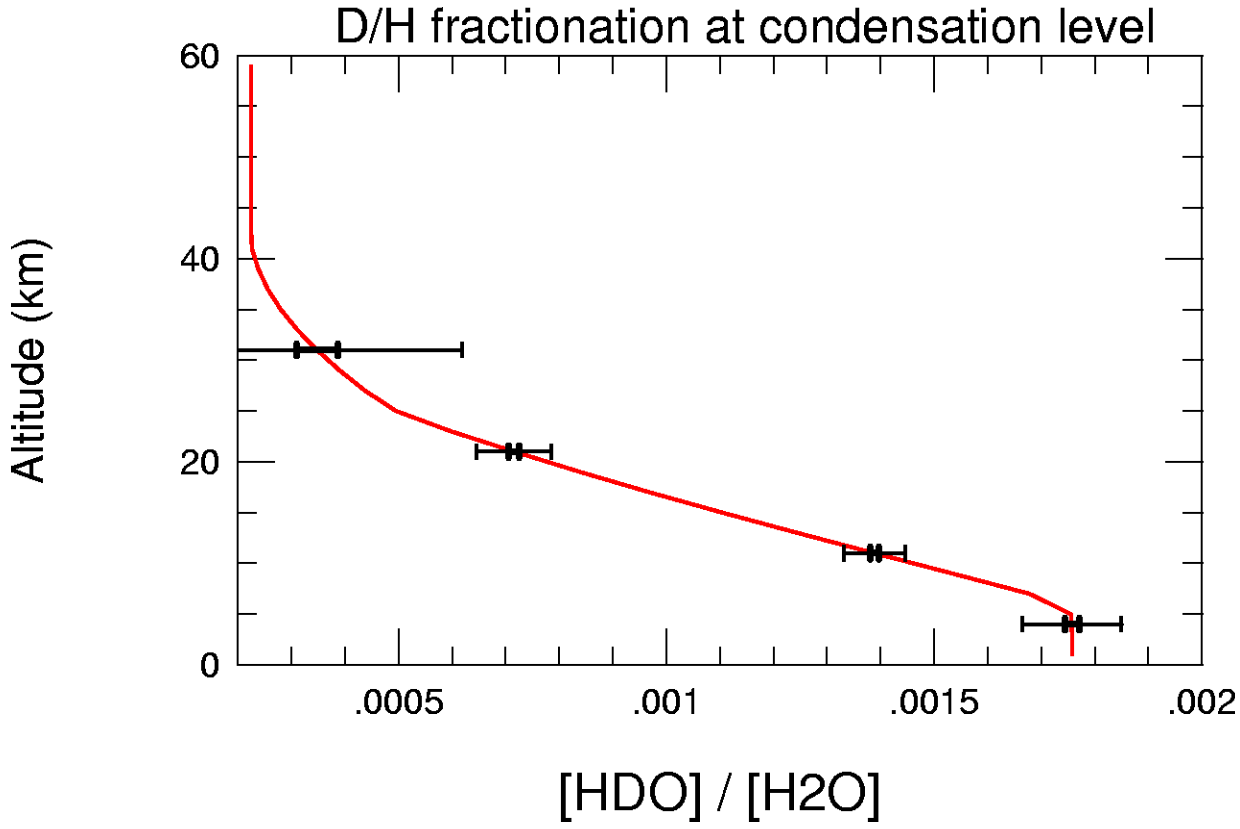


Relative RMS accuracy (%)



Based on Simulation performed with MOLIERE, Obs de Bordeaux

4) 3D mapping of D/H ratio



- **Vertical, horizontal, Seasonal variations**
  - **Strong fractionnation at condensation level** (*Bertaux and Montmessin, 2002, Fouchet and Lellouch 2001*)
  - **Detection of ground reservoir signature ?**
- **Determination of a reference value for Mars**

→ ***Cloud microphysic & Water cycle***

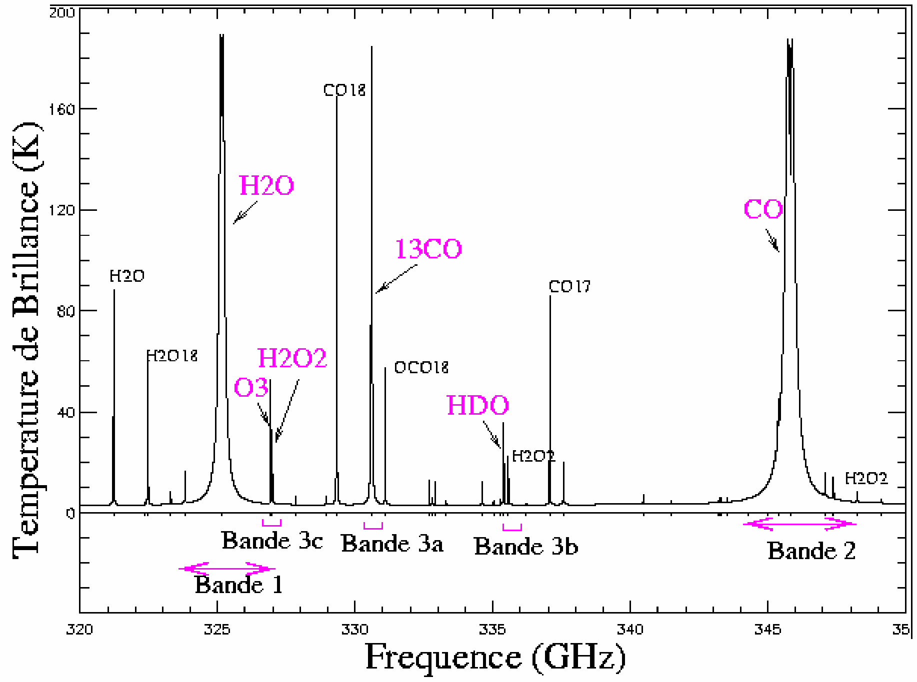
→ ***Study of escape processes & volatile evolution***

5) 3D mapping of H2O2

- Key molecule
  (H2, O2, CO regulation)
- Recently been detected !

(Clancy et al. 2004, Encrenaz et al. 2004)

- Surface oxydation => Exobiology



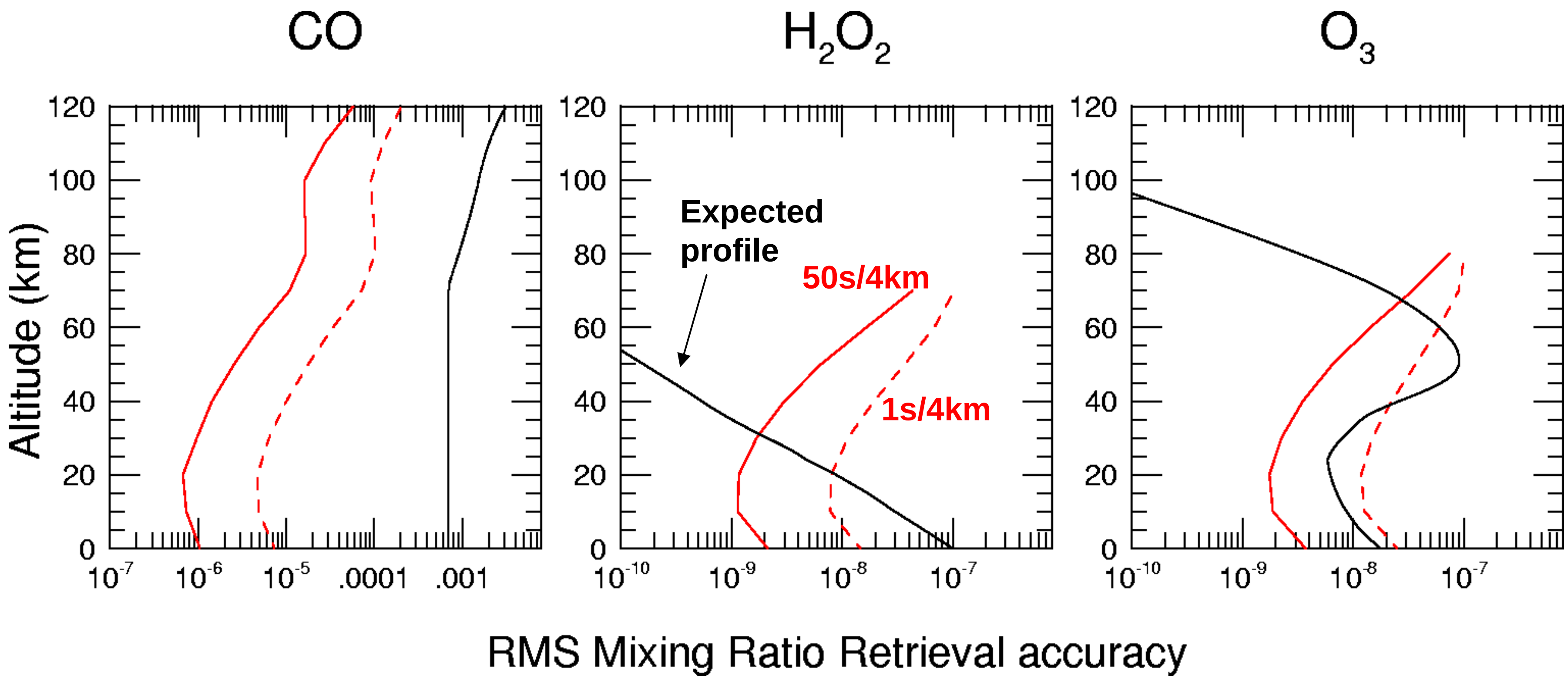
6) 3D mapping of O3

- up to 70 km
- simultaneously with H2O

7) 3D mapping of CO

=> A complete view of Mars photochemisrty

Retrieval of chemical species



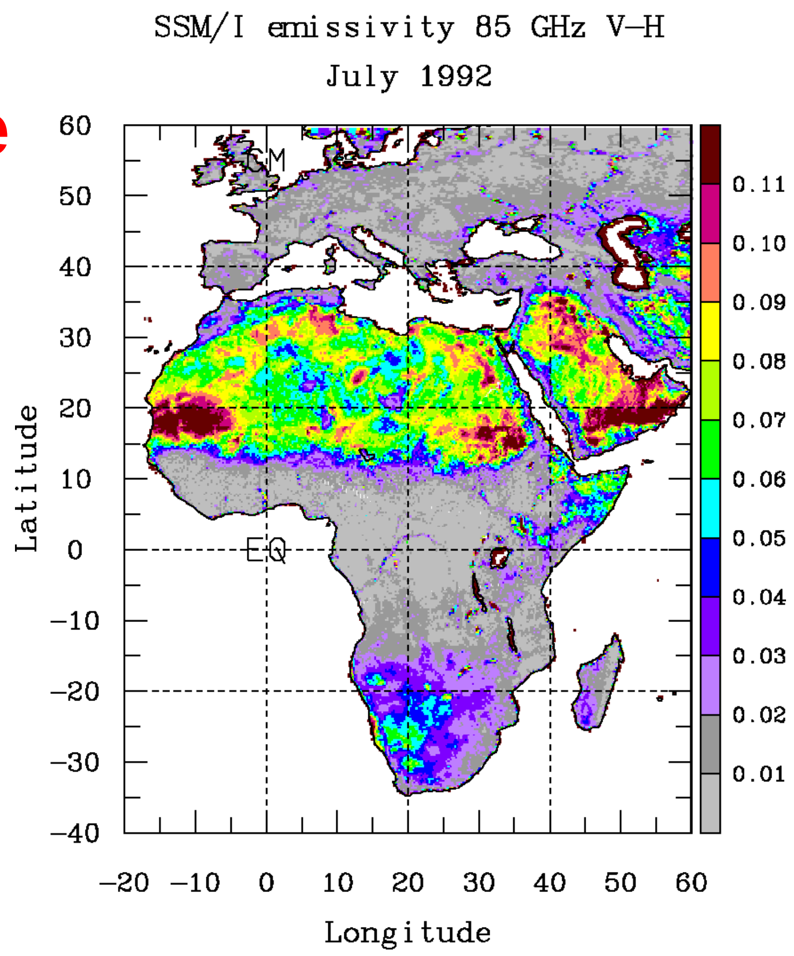
8, 9, 10, 11) : Surface Science

Mapping of the surface microwave emission and will map the variations due to:

1) subsurface ice contents (1-20 mm)
2) surface roughness (10-100 m horizontal scale)
3) CO2 ice cap characteristic
4) temperature sensing depth

Method:

• H and V polarization
• Same point observed with various viewing Angle and at different local time



Example: surface roughness Mapping at 85 GHz (Prigent et al. 1997).

12) Magnetic field

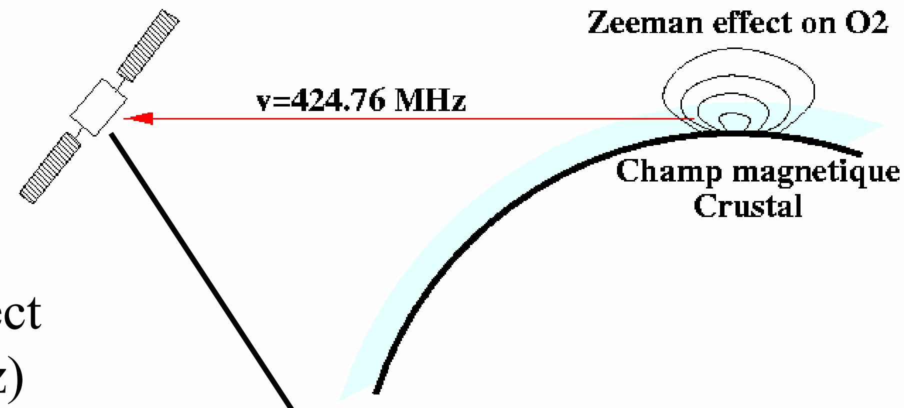
(Option ???)

- Detectiion of the «Zeeman» effect in the O2 emission (424.76 MHz)

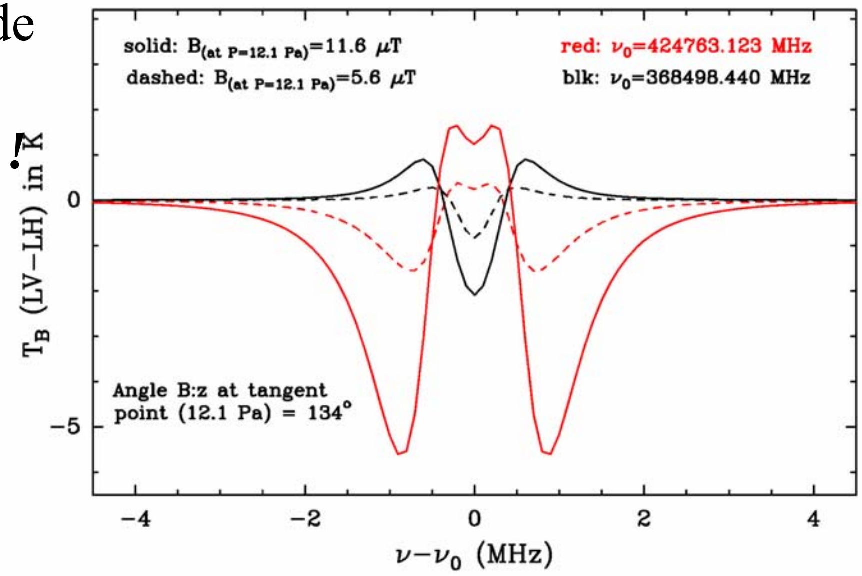
- *In practice :* measurement of the difference between vertical and horizontal polarization between 30 et 60 km d'altitude

=> ***Mapping of the crustal magnetic field !***

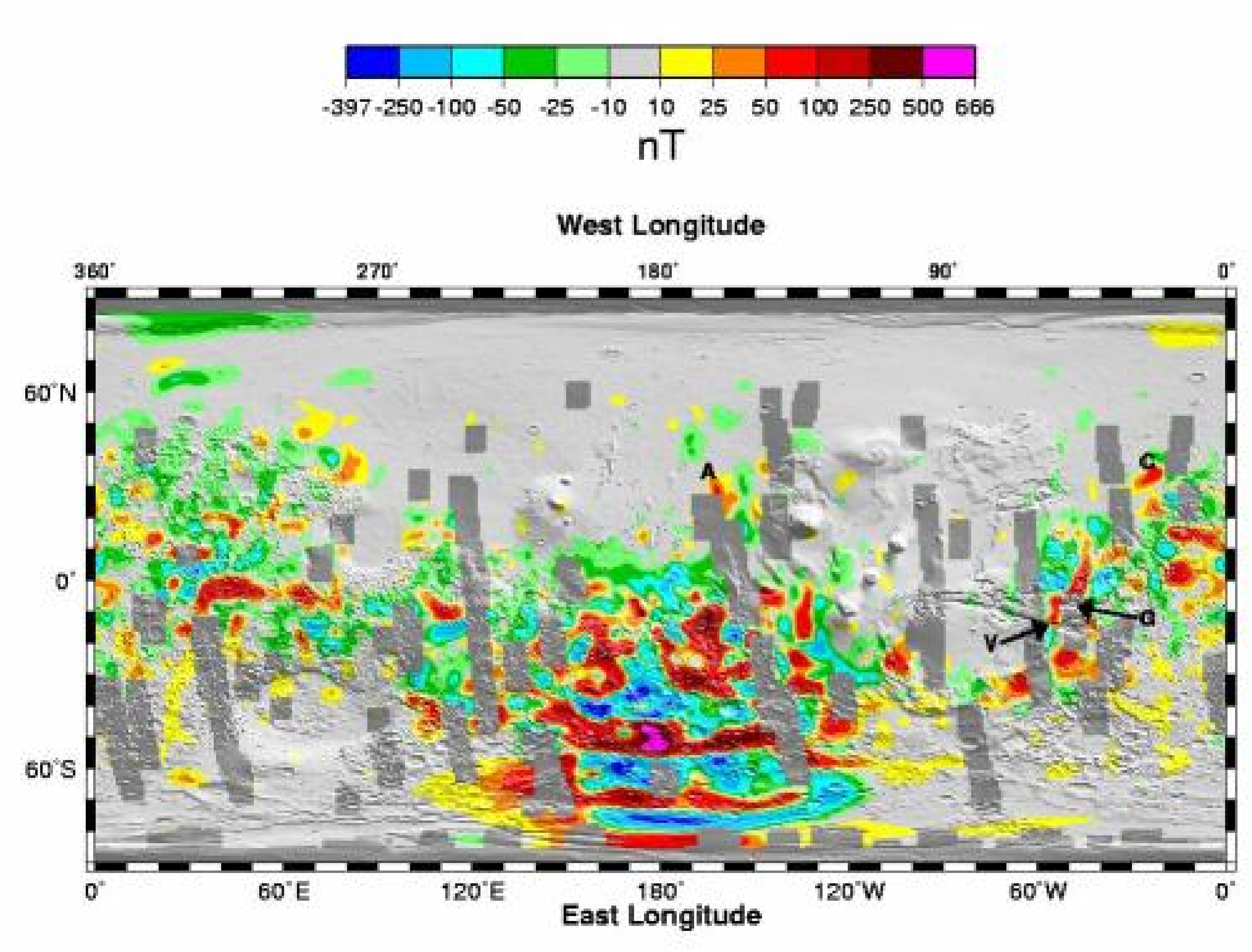
- Résolution : ~50 km ? 200 km ?
- Accuracy < 1 micro-Tesla ?



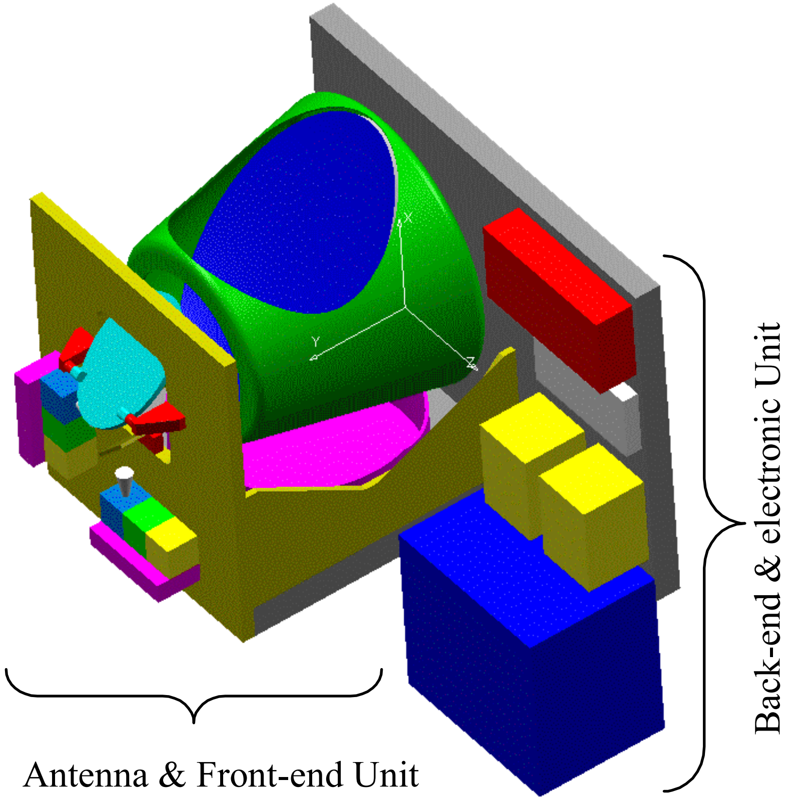
Calculations by Juan Pardo

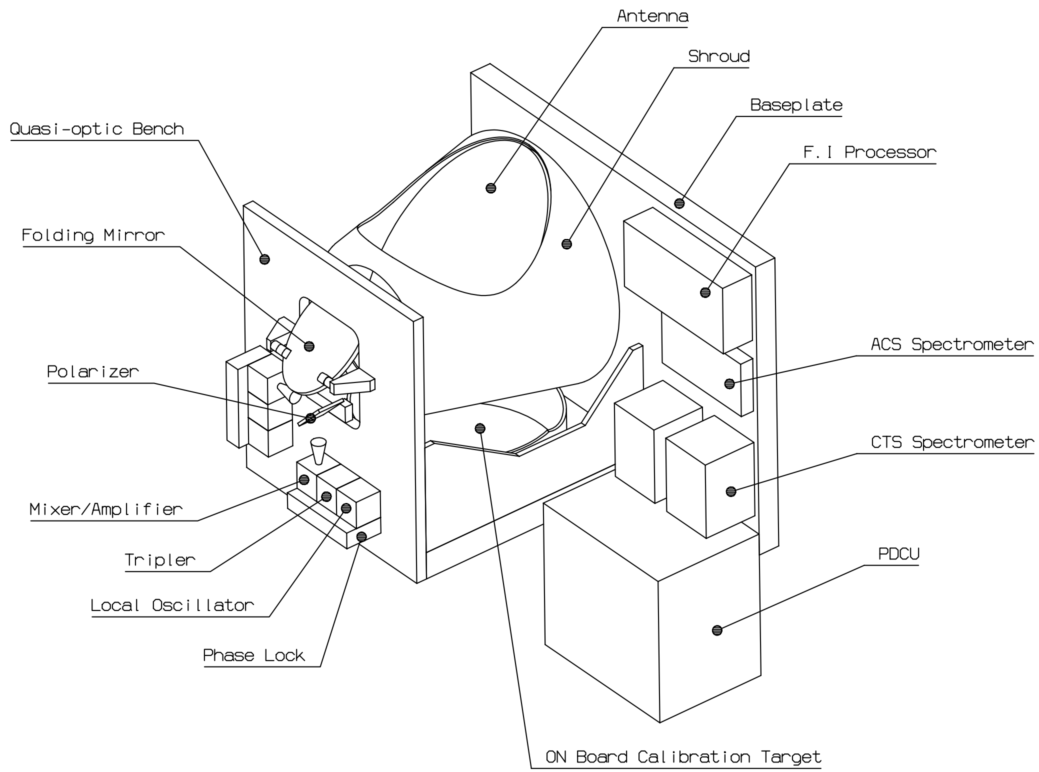


Magnetic Map of Mars, altitude=200 km (Purucker et al., 2000)



MAMBO Instrument

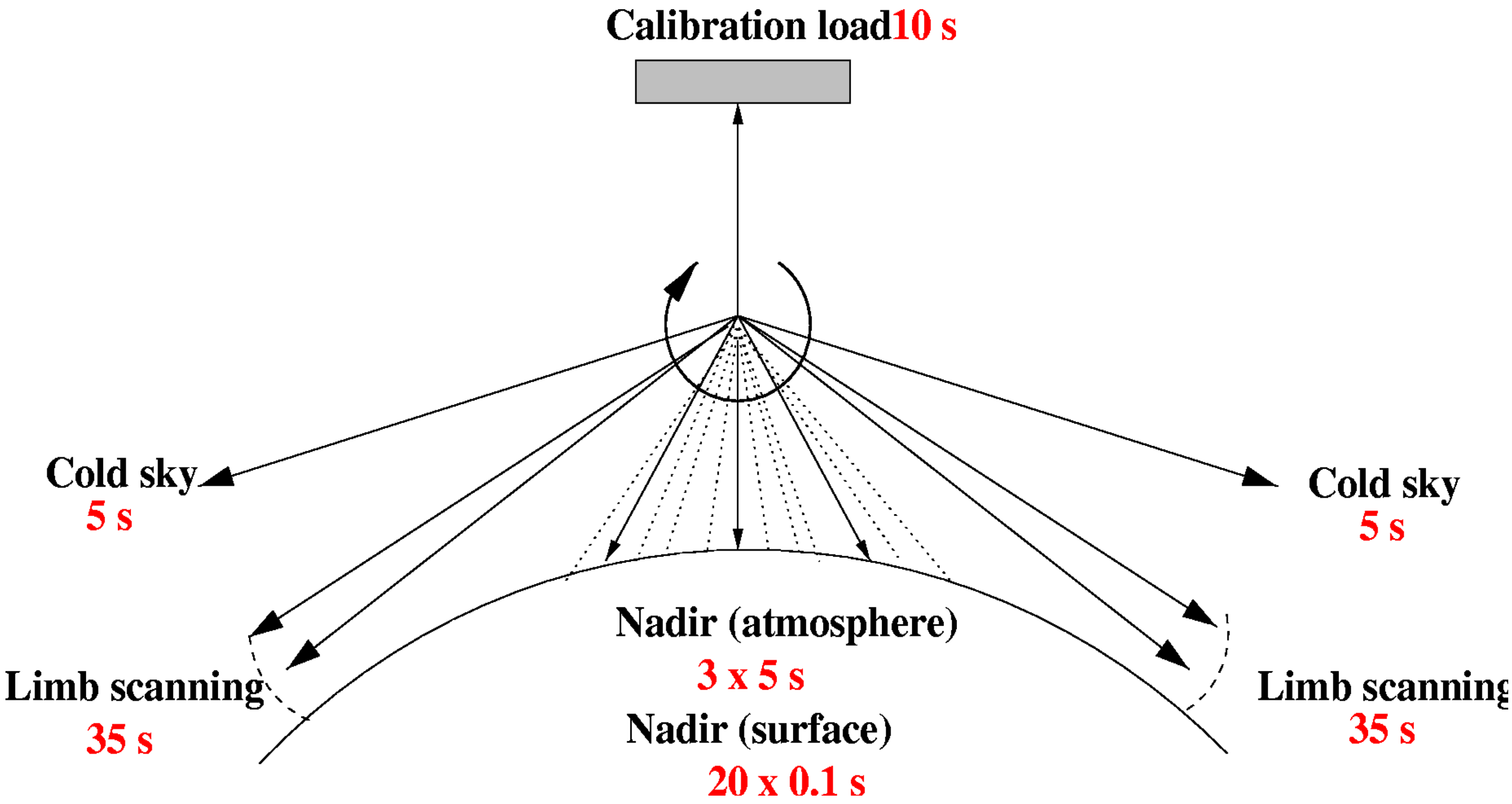




Design : ASTRIUM

Receiver frequency	323 – 347 Ghz
System Temperature DSB	1500 K
Maximal spectral resolution	100 kHz
Antenna aperture	23 cm (*)
Antenna beam width at limb	~8 km (*)
Mass (20% margin included)	27.8 kg
Power (margin included)	62.5 W
Data rate to Earth)	35 to 50 Mbits/day

MAMBO observation strategy



Total sequence : 110 s

MAMBO observation strategy

[MARS] MAMBO
Trace de l'orbite

>>> Durée représentée : 240.0 min = 0.16 sol

Trace des fauchées orthogonales

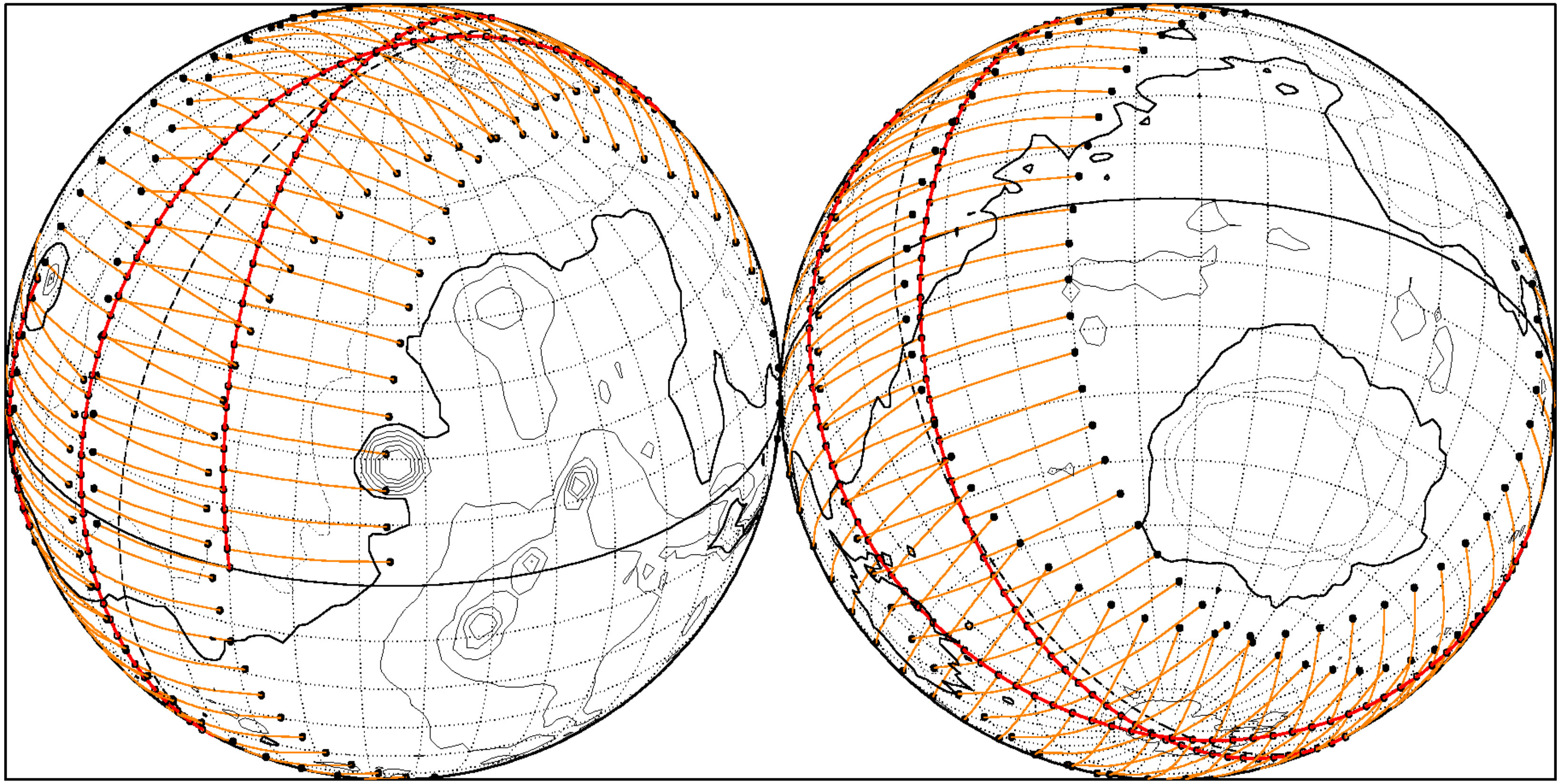
Altitude = 350.0 km a = 3746.200 km

Inclinaison HELIOSYNCHRONE = 92.86 °

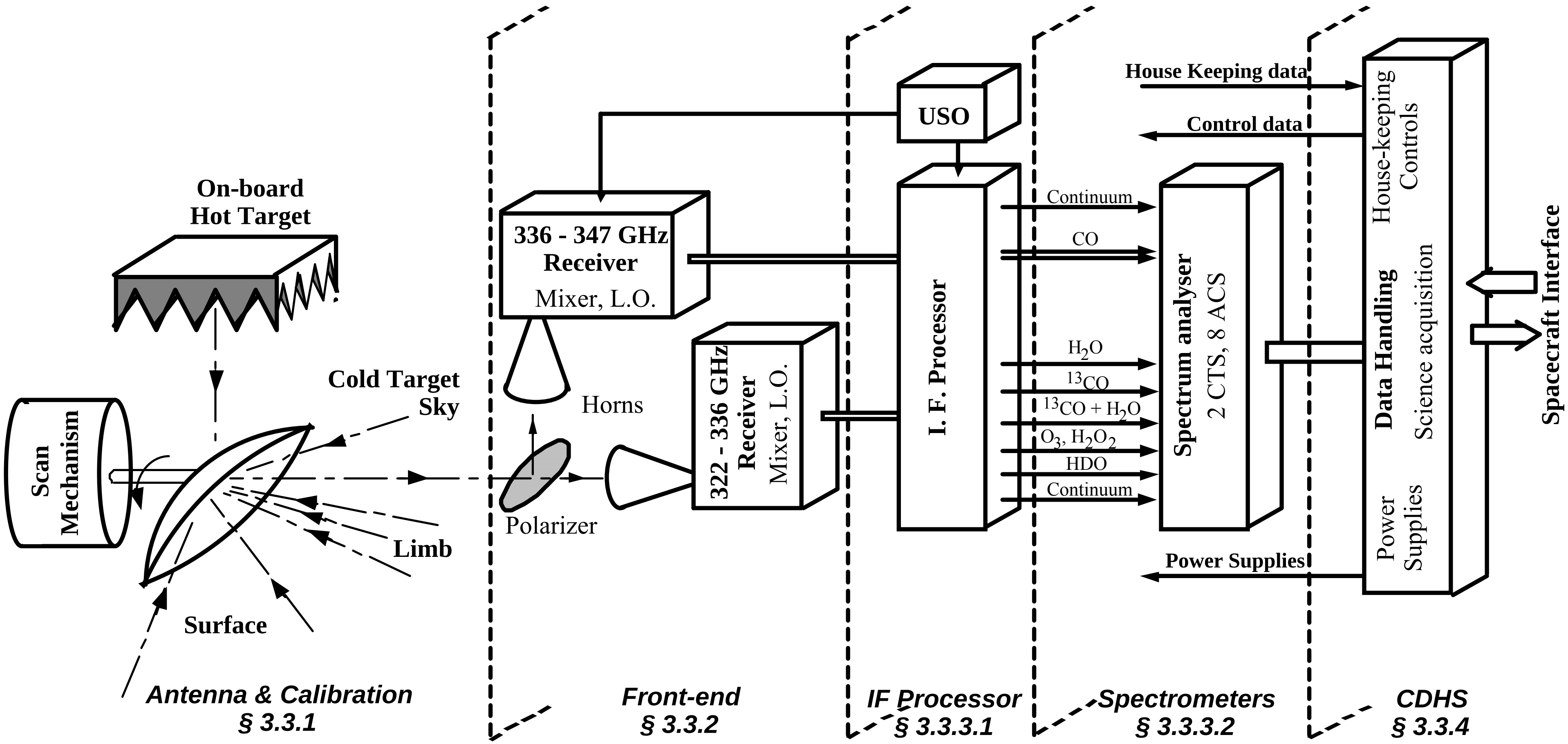
Période = 116.30 min * Trs/sol = 12.72

Décalage à l'équateur = 1677.4 km (28.3 °)

** Demi-fauchée : 65.0° => 1479 km [1.0 min]



MAMBO Functional Diagram



MAMBO Instrument and team

- **PI** : F. Forget (LMD)
- **Hardware development** :
  - Management : Paris Observatory, LERMA (G. Beaudin, A. Deschamps, M. Gheudin)
  - IF processor : JPL (USA) (M. Janssen, L. Riley, P. Frerking, S. Gulkis)
  - CTS Spectrometers: MPAE (Germany) (P. Hartogh)
  - ACS spectrometers: SSC/Omnisys (Sweden)

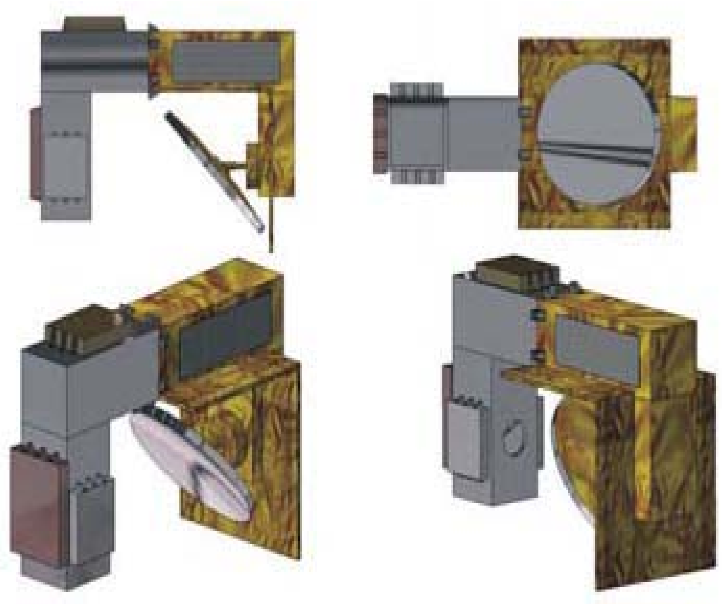
- **Science teams**
  - IPSL : LMD (M. Capderou, K. Dassas, S. Lebonnois) , SA (F. Lefevre, F. Montmessin)
  - Paris Observatory : LESIA (T. Encrenaz, E. Lellouch) , LERMA (C. Prigent, P. Encrenaz)
  - Bordeaux Observatory (P. Ricaud, J. Urban)
  - MPAE (Germany) (W. Markiewicz)
  - JPL, Caltech (M. Allen, M. Richadson), SSI (T. Clancy), NASA Ames (B. Haberle) (USA)….

Other Mars projects

- Proposal for Mars Observer (~1985. PI D.Muelhman). 220-230 Ghz

- MIME (1999) proposed for Mars Express (*PI : P. Hartogh*) 575 GHz

⇨ current concept “SWI”



SWI

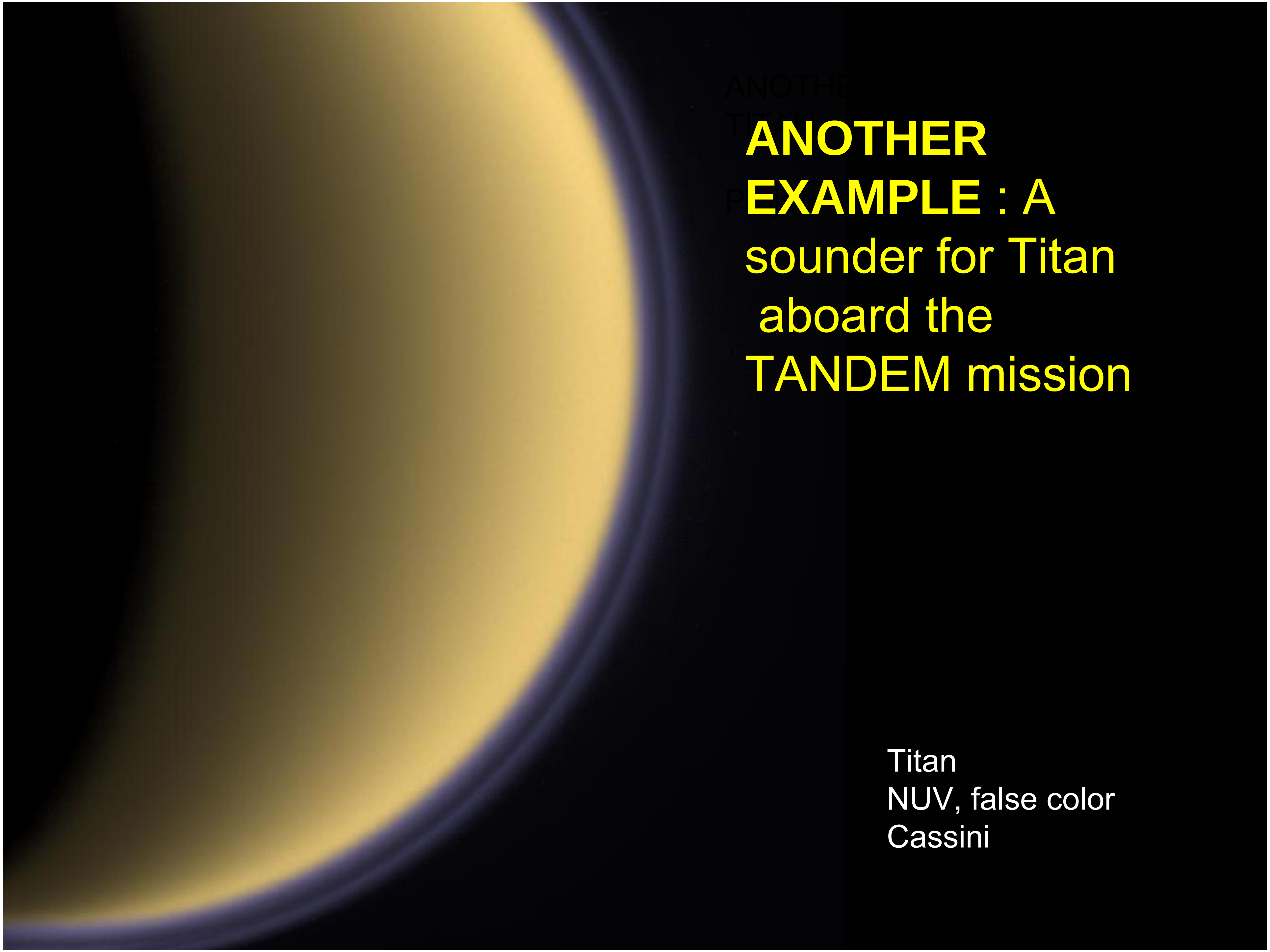
The future of microwave sounding on Mars

New technologies :

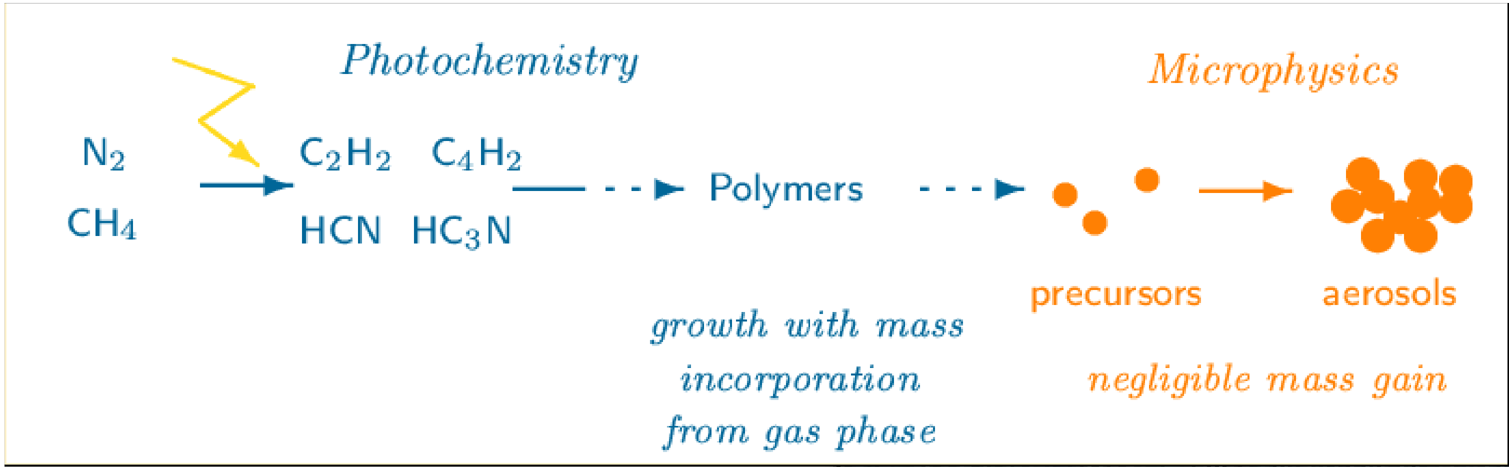
- Use higher frequencies ?
- Tunable receivers (frequency scanning with a synthetizer) to look for minor constituent or simplify the instrument
- Cooled instrument ???

Upcoming opportunities

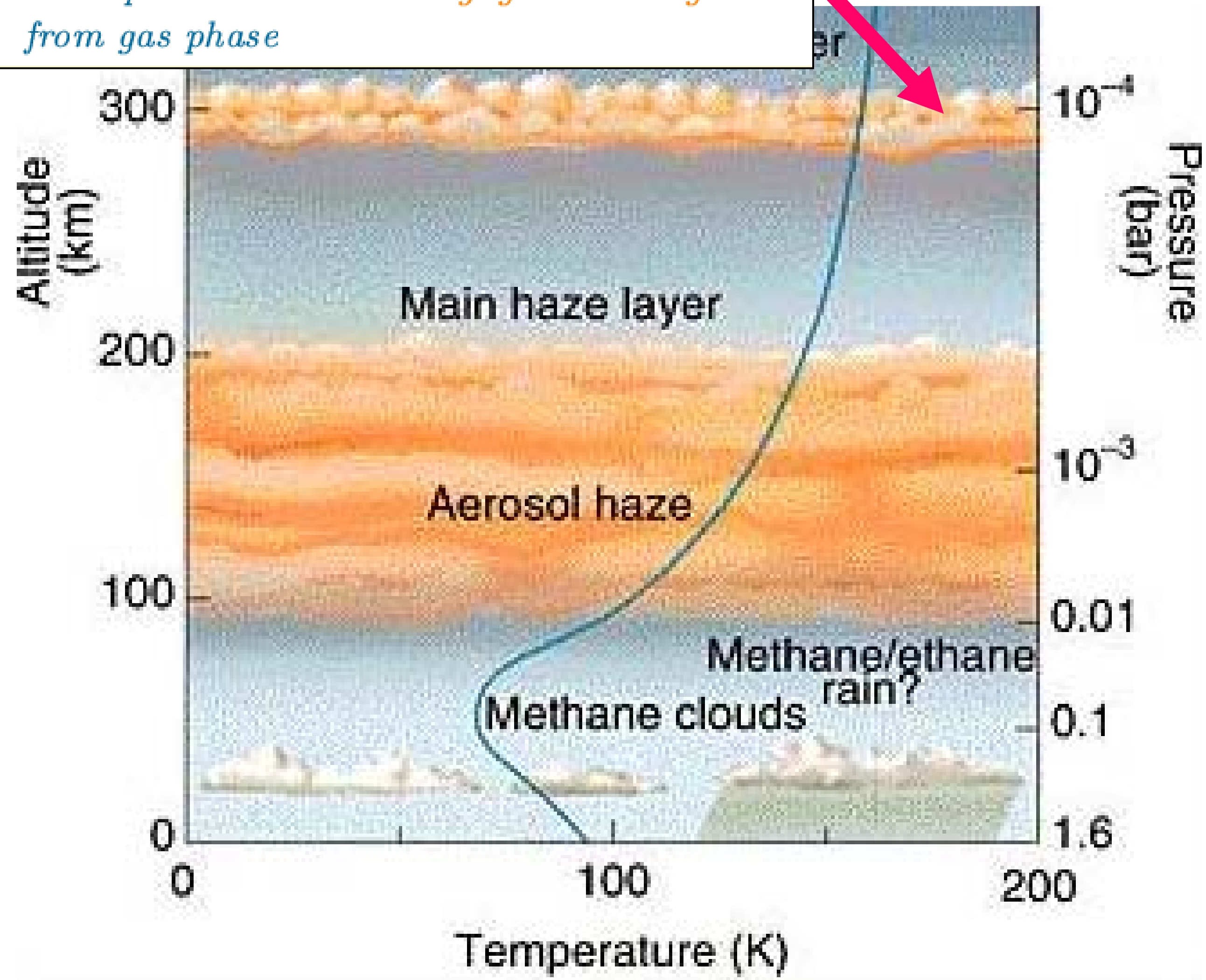
- Next ESA orbiter : Mars Next in 2016. Includes a 15 kg microwave sounder in its strawman payload. ***Won't happen***
- Next NASA orbiter (after 2013 selected Maven) : Mars Science Orbiter (2018). Includes a 30 kg microwave sounder in its strawman payload !
- Japan (2016-2018) ?


ANOTHER EXAMPLE : A sounder for Titan aboard the TANDEM mission
Titan
NUV, false color
Cassini

Titan :



Photochemistry
Microphysics
N2
CH4
C2H2 C4H2
HCN HC3N
Polymers
precursors
aerosols
growth with mass
incorporation
from gas phase
negligible mass gain



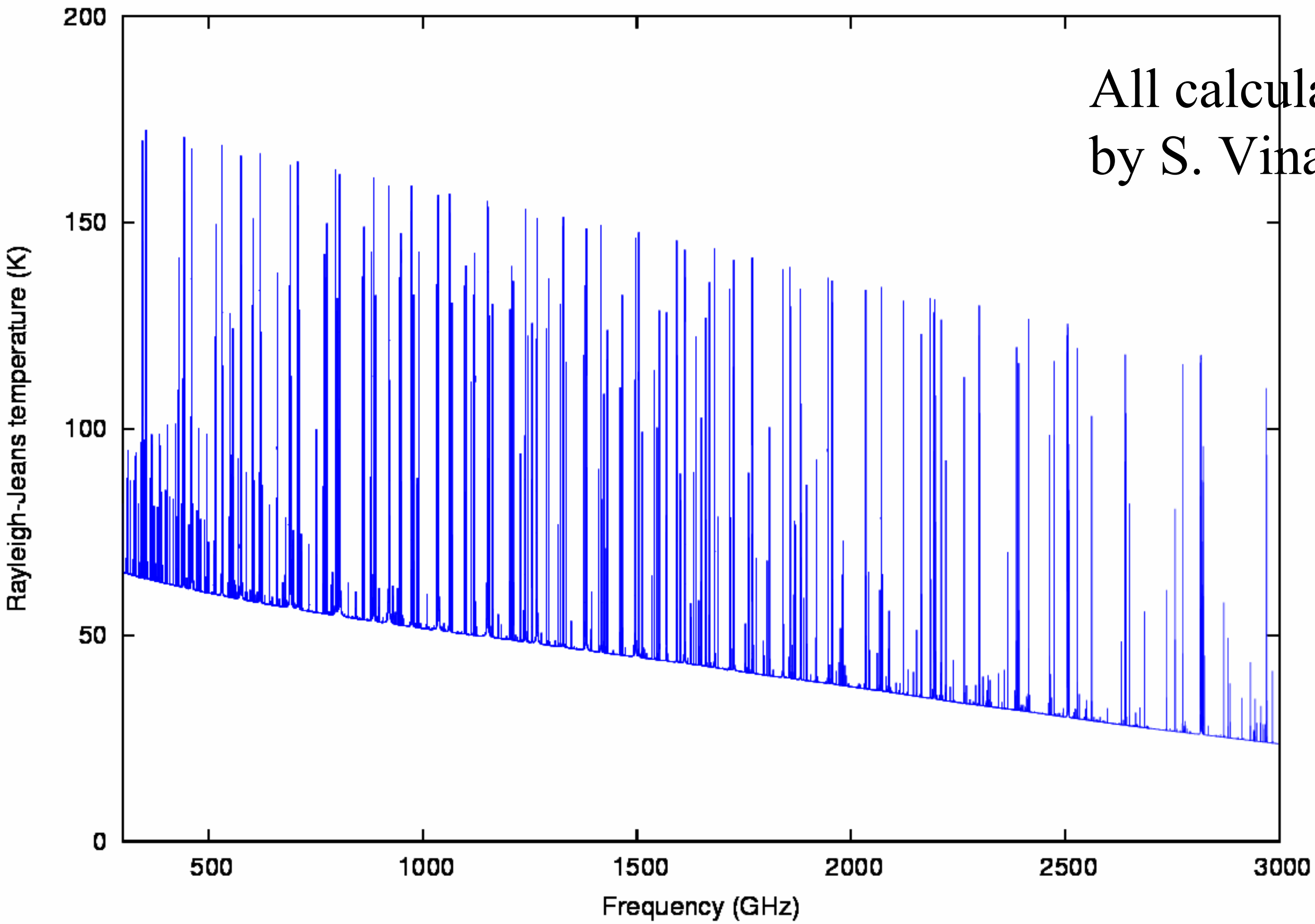
Altitude (km)
300
200
100
0
Main haze layer
Aerosol haze
Methane/ethane rain?
Methane clouds
Pressure (bar)
10^-4
10^-3
0.01
0.1
1.6
0
100
200
Temperature (K)

The case for a submillimeter sounder on the TSSM Titan Orbiter

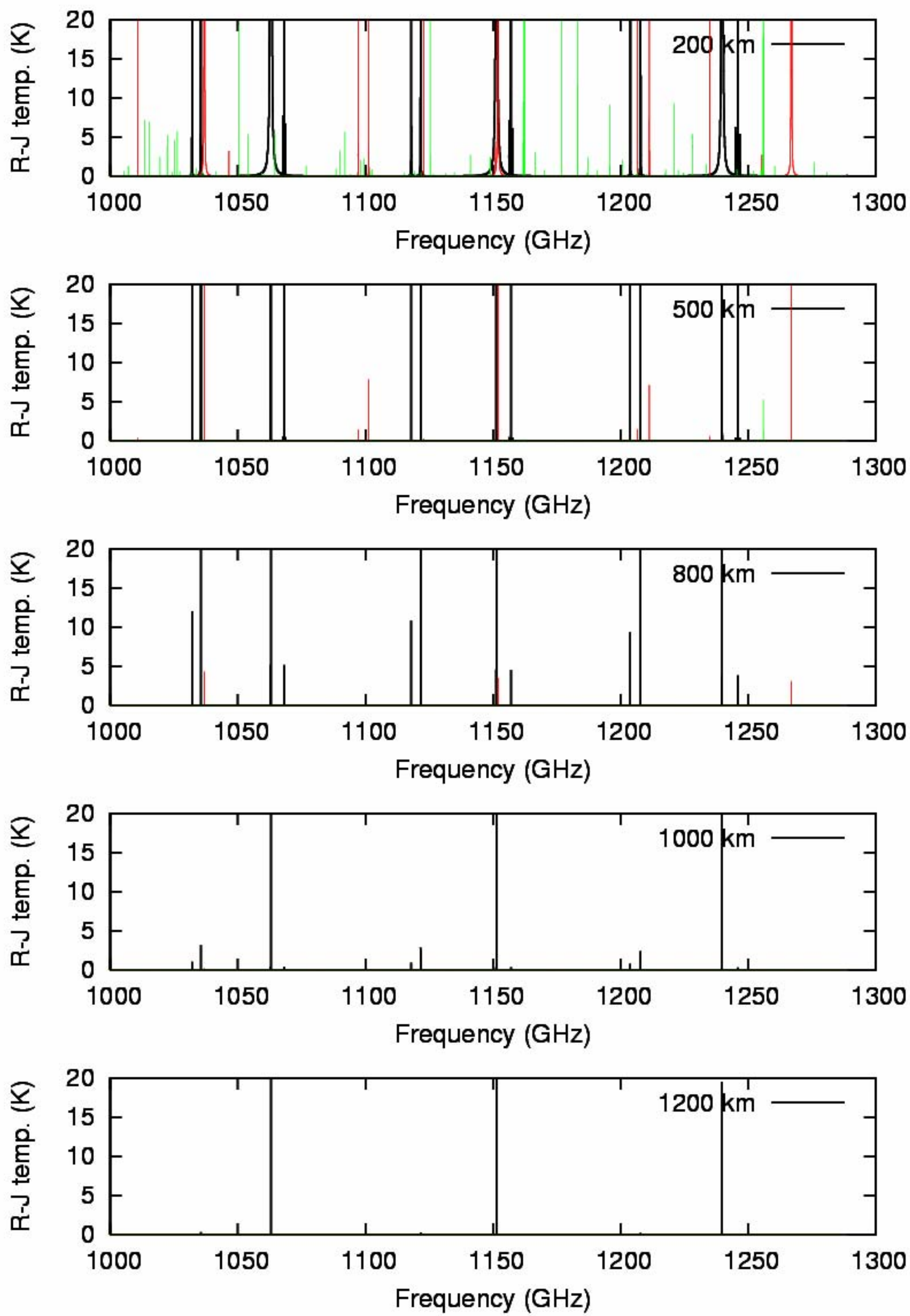
E. Lellouch, S. Vinatier, P. Hartogh,
G. Beaudin, R. Moreno, …, et al.

Presented at TSSM meeting Meudon, 19 March 2008

A model of Titan's (nadir) spectrum as seen by a heterodyne spectrometer



All calculations by S. Vinatier



Titan’s expected spectrum at 1.0-1.3 THz

HCN CO CH4

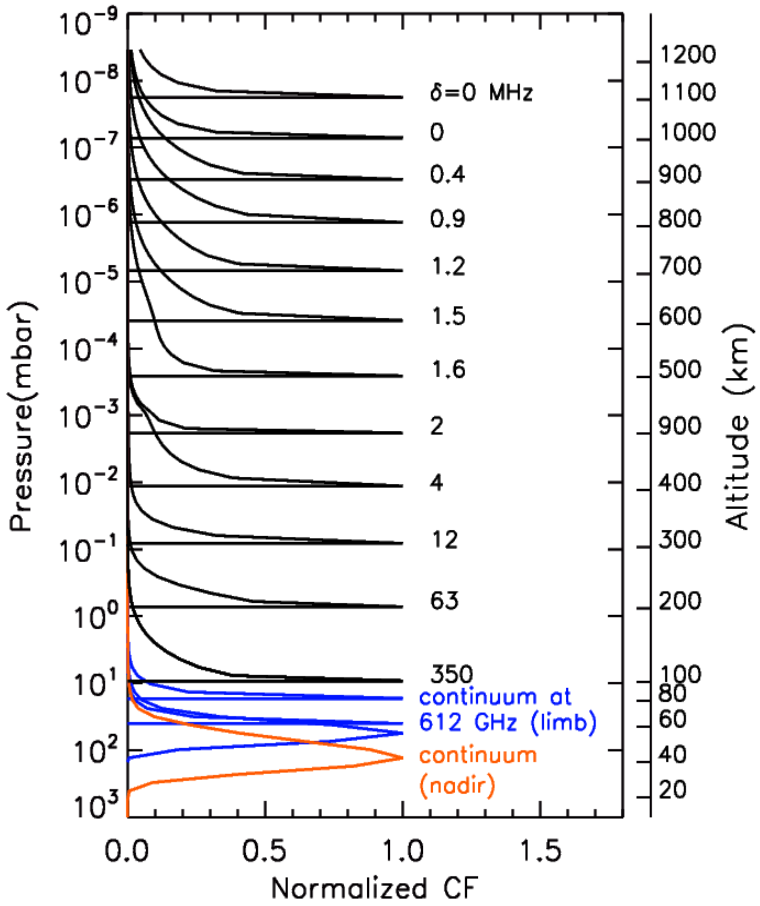
Thermal sounding

- From CH_4 (uniform) : up to ~500 km
- From CO (almost certainly uniform) ; no homopause uncertainty problem: up to ~800 km
- From HCN (not uniform vertically nor spatially, but feasible through multiple lines incl. isotopes, cf. CO on Venus) : up to ~1200 km

- Advantage: *LTE is not a major issue like in IR*
- vertical resolution ~ 8 km (width of contribution functions)
- expected precision ΔT ~1 K in 1 min observation

Science goal # 1: Temperature sounding

- **Approach: use HCN, CO and CH4 to retrieve T(z)**
- CO and CH4 probe atmosphere up to ~800 and ~400 km respectively and are horizontally/vertically uniform in range of interest.
- HCN is not uniform but optically thick up to 1150 km; combination with INMS-like instrument possible higher up.
- **Advantages:**
- good sampling of 40-1200 km range
- vertical resolution ~ 8 km (width of contribution functions)
- expected precision ΔT ~1 K in 1 min observation
- **rotational LTE** valid to very high altitudes (typically ~ 10-11 bar ~1250 km)



Science goal #2: Direct wind measurements

- .
- **Approach:** *Direct absolute* wind measurements from Doppler shift on any optically thin line. **Advantages**:
- No assumption on thermal field equation validity
- or boundary condition
- Precision 3-4 m/s for $\Delta T \sim 100$ K contrast line in 1-min
- Possibility to measure zonal winds (off-track from polar orbit) and meridional wind (in-track)

Science goal #3: Chemistry and coupling with dynamics

- **Goals: 1)** determine vertical/horizontal distribution of several
- minor species with various chemical lifetimes (HCN, HC3N, CH3CN, CH3CCH,
- H2O) and relate it to the global wind field (and possibly to source of oxygen).
- **2)** Search for species yet undetected in stratosphere/mesosphere (HC5N, C2H3CN,
- NH3, CH2NH) and compare chemical complexity to thermosphere as seen by INMS.
- **3)** Determine yet un-established isotope ratios (16O/18O in CO, D/H in HCN and H2O).

Preliminary instrument characteristics

- D= 15 cm-antenna with articulation system, allowing limb and nadir sounding
  - In track-views needed for meridional winds and to perfom limb sounding over poles
  - Off-track views needed for zonal winds
- Two receivers sharing common and tunable LO system
  - 1 “high-frequency” band (e.g. 540-640 GHz; or 1080-1280 GHz)
  - 1 “low-frequency” band (e.g. 300-360 GHz band)
- Typical spatial /vertical resolution ~ 4 mrad @ 600 GHz (⇔ 8 km @ 2000 km)
- Instantaneous bandwidth: 1 GHz @ 300 kHz resolution
- Uncooled Schottky receivers: Tsys (DSB) ~6000 K at 1 THz, ~4000 K at 600 GHz, 2500 K at 350 GHz
- Typical performances: ΔT (1 σ) in 1 MHz = 0.6-1.5 K in 1 min; 0.08 K -0.2 K in 1 hour
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Conclusions

- Limb Sub-mm atmospheric sounding will be used in future planetary missions
- Key objectives : Doppler winds, temperature, trace species
- Need for wide band / tunable receivers to monitor several lines with a light instrument
- Key compromise : Noise/antenna size/gas lines target/vertical resolution
  - ⇨need to define acquisition time when designing/comparing concepts.